SORELMETAL®

DUCTILE IRON DATA

for Design Engineers

Published by :

RIO TINTO IRON & TITANIUM INC.
770 Sherbrooke Street West
Suite 1800
Montreal, Quebec , Canada
H3A 1G1

Sorelmetal® is produced by
QIT - Fer et Titane Inc., Sorel, Canada and Richards Bay Minerals, South Africa

Ductile Iron Data

for Design Engineers

TABLE OF CONTENTS

PREFACE

Ductile Iron Data for Design Engineers revised edition. The title describes both the contents and the objective of this book. It is a comprehensive summary of data describing the engineering properties of Ductile Iron. The youngest but most successful member of a truly ancient family, Ductile Iron has suffered from an abundance of myths and a lack of information.

"Cast iron is brittle." is an outdated but widely held truism which mistakenly implies that all cast irons are the same, and none are ductile. In fact, Ductile Iron is far more than a cast iron which is ductile. It offers the design engineer a unique combination of a wide range of high strength, wear resistance, fatigue resistance, toughness and ductility in addition to the well-known advantages of cast iron – castability, machinability, damping properties, and economy of production. Unfortunately, these positive attributes of Ductile Iron are not as widely known as the mistaken impression of brittleness is well known.

The purpose of this book, therefore, is quite simple: to replace the myths with data, and let the designer decide how he can take advantage of the unique combination of properties offered by Ductile Iron.

This book is being offered to design engineers through the Ductile Iron Marketing Group (DIMG), a non-profit organization whose goal is the promotion of the generic use of Ductile Iron castings through market surveys and promotional and educational activities. It has been published by Rio Tinto Iron & Titanium Inc. (formerly QIT - Fer et Titane Inc.), a member and co-founder with Miller and Company of the DIMG. The other member of the group is the Ductile Iron Society (DIS). Dr. Richard Warda, formerly with QIT and CANMET originally wrote the book.

Significant editorial assistance and additional materials were provided by Mr. L. Jenkins, Technical Director, DIS; Dr. G. Ruff, CMI Tech. Center; John Keough & Bela V. Kovacs, Atmosphere Furnace Company; Mrs. F. Dubé, Rio Tinto Iron & Titanium Inc.

Rio Tinto Iron & Titanium Inc. (RIT), has made every reasonable effort to ensure that the data presented accurately represents the information contained in the many sources from which it was obtained and, when necessary, attempts have been made to reconcile data from different sources which do not agree. Therefore RIT believes that all information given is accurate and is provided in good faith, but without any warranty, either express or implied.

James D. Mullins
Manager,
Sorelmetal Technical Services
Rio Tinto Iron & Titanium Inc.

SECTION I

FORWARD

SECTION I

FORWARD

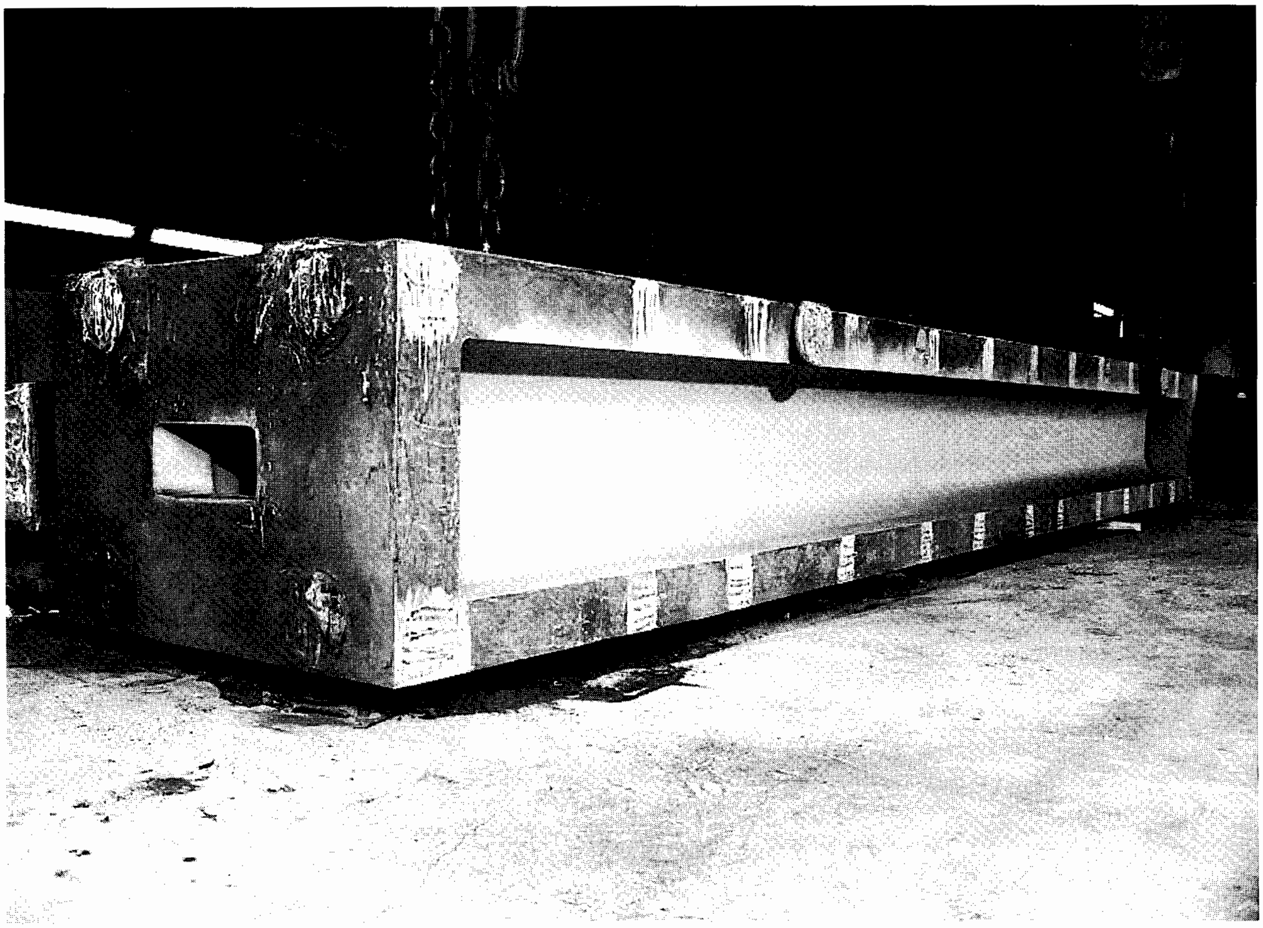
Over forty years ago the birth of a new engineering material, Ductile Iron, was announced at the 1948 American Foundrymen's Society Annual Conference. Looking back on the first four decades of Ductile Iron reveals the classical pattern of the research, development and commercialization of a new material. In the early years INCO, the patent holder, introduced Ductile Iron to designers and engineers by distributing technical literature and conducting seminars. As knowledge of the properties and economies of Ductile Iron spread, its usage increased dramatically throughout the fifties and early sixties. After the termination of INCO's promotion of Ductile Iron in 1966, Ductile Iron market growth continued to outperform other ferrous castings but, as the engineers and designers who benefitted from the early promotional efforts of INCO retired and were replaced by a new generation, the knowledge gap about Ductile Iron began to widen.

During the past decade the development and commercialization of austempered Ductile Iron (ADI) has added a new star to the Ductile Iron family. Combining the strength, ductility, fracture toughness and wear resistance of a steel with the castability and production economies of a conventional Ductile Iron, ADI offers the designer an exceptional opportunity to create superior components at reduced cost. Only one factor has detracted from this story of forty years of Ductile Iron technology – the promotion of this material to designers has been a poor second to its technical development. In fact, the lack of knowledge and understanding among some potential users about the properties and uses of Ductile Iron is astounding.

In 1985 QIT-Fer et Titane and Miller & Company, two suppliers to the Ductile Iron foundry industry, recognized that a lack of engineering data was inhibiting the sales of Ductile Iron castings. To remedy this lack of information, QIT and Miller & Company formed the Ductile Iron Group (DIG). For the past five years, the DIMG, which also includes the Ductile Iron Society, have conducted market surveys to identify the informational needs of designers and engineers and have addressed these needs through the publication of technical literature and the presentation of technical lectures and seminars.

"Ductile Iron Data for Design Engineers" (revised edition), produced by Rio Tinto Iron & Titanium for distribution by the Ductile Iron Marketing Group, will help to overcome the lack of information which has persisted, even after forty years of Ductile Iron production. By informing designers and engineers about the impressive mechanical properties and economic advantages of Ductile Iron and ADI, this book should be of significant benefit to both users and producers of this remarkable material.

Keith D. Millis (deceased)
Formerly Executive Director
Ductile Iron Society
& Co founder of Ductile Iron



Courtesy of Siempelkamp Guss, Germany

World's largest Ductile Iron casting produced to date: crosshead for pipe press. Net casting weight 230 tonnes. Length: 14m, height: 2m and width: 2.5m.

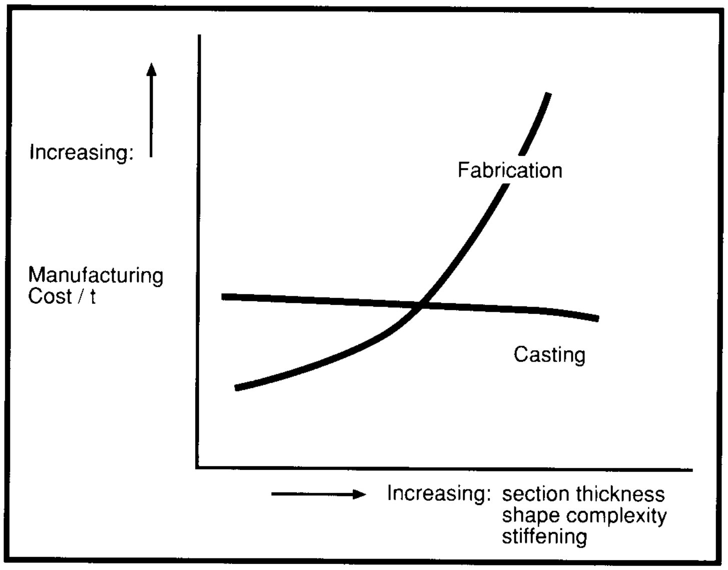
This casting contains 80 tonnes of Sorelmetal in order to obtain the excellent properties required in the heaviest sections.

SECTION II

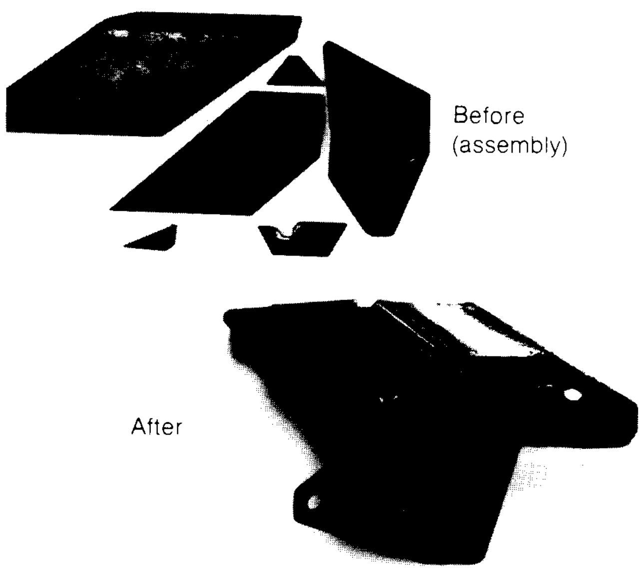
INTRODUCTION

SECTION II

Figure 2.1



Schematic cost comparison between fabricated and cast components.



Courtesy: Ferrovorm, Republic of South Africa

Mounting bracket on a mold board plow produced by Fedmech Holdings Limited. The reason for switching to a grade 72,500 p.s.i. (500 mPa) Ductile Iron casting was the many field failures of the heavily welded steel part. Repeated attempts to improve the fabricated design resulted in too many components which led to warping and dimensional accuracy problems during welding. There was also a high reject level during fabrication of the part.

INTRODUCTION

The Casting Advantage

The casting process has been used for over 5000 years to produce both objects of art and utilitarian items essential for the varied activities of civilization. Why have castings played such a significant role in man's diverse activities? For the artist, the casting process has provided a medium of expression which not only imposed no restrictions on shape, but also faithfully replicated every detail of his work, no matter how intricate. Designers use the same freedom of form and replication of detail to meet the basic goal of industrial design – the matching of form to function to optimize component performance. In addition to design flexibility, the casting process offers significant advantages in cost and materials selection and performance.

Design Flexibility

The design flexibility offered by the casting process far exceeds that of any other process used for the production of engineering components. This flexibility enables the design engineer to match the design of the component to its function. Metal can be placed where it is required to optimize the load carrying capacity of the part, and can be removed from unstressed areas to reduce weight. Changes in cross-section can be streamlined to reduce stress concentrations. The result? Both initial and life-cycle costs are reduced through material and energy conservation and increased component performance.

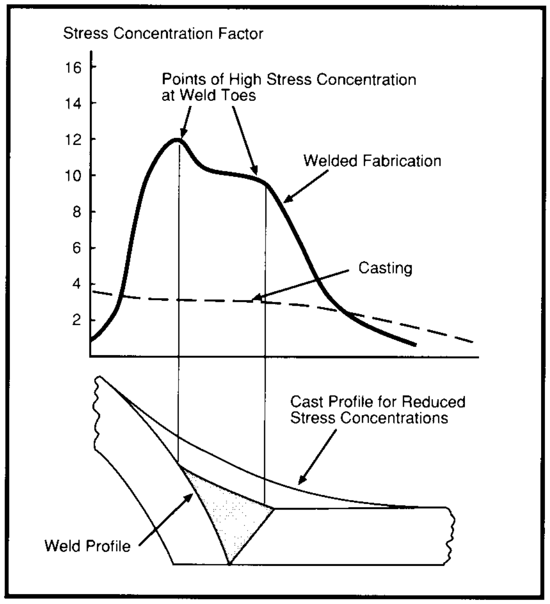
Designer engineers can now optimize casting shape and performance with increased speed and confidence. Recent developments in CAD/CAM, solid modelling and finite element analysis (FEA) techniques permit highly accurate analyses of stress distributions and component deflections under simulated operating conditions. In addition to enhancing functional design, the analytical capabilities of CAD/CAM have enabled foundry engineers to maximize casting integrity and reduce production costs through the optimization of solidification behaviour.

Reduced Costs

Castings offer cost advantages over fabrications and forgings over a wide range of production rates, component size and design complexity. The mechanization and automation of casting processes have substantially reduced the cost of high volume castings, while new and innovative techniques such as the use of styrofoam patterns and CAD/CAM pattern production have dramatically reduced both development times and costs for prototype and short-run castings. As confidence in FEA techniques increases, the importance of prototypes, often in the form of fabrications which "compromise" the final design, will decrease and more and more new components will go directly from the design stage to the production casting.

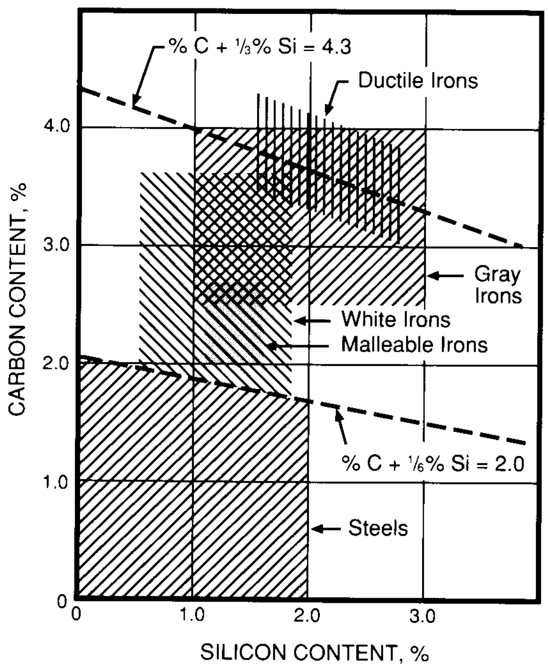
As shown in Figure 2.1, as component size and complexity increase, the cost per unit of weight of fabricated components can rise rapidly, while those of castings can actually decrease due to the improved

Figure 2.2



Acrylic model stress analyses of a welded fabrication and a casting.

Figure 2.3



Approximate ranges of carbon and silicon for steel and various cast irons.

castability and higher yield of larger castings. Near net shape casting processes and casting surface finishes in the range 50-500 microinches minimize component production costs by reducing or eliminating machining operations.

Replacement of a multi-part, welded and/or fastened assembly by a casting offers significant savings in production costs. Inventory costs are reduced, close-tolerance machining required to fit parts together is eliminated, assembly errors cannot occur, and engineering, inspection and administrative costs related to multi-part assemblies are reduced significantly. A recent study by the National Center for Manufacturing Sciences (NCMS) has shown that in certain machine tool applications, the replacement of fabricated structures by Ductile Iron castings could result in cost savings of 39-50%. Commenting on the NCMS study, Mr. Gary Lunger, President of Erie Press Inc., stated:

"We make huge presses and we have relatively clear specifications for what goes into each press. We have been able to use Ductile Iron as a substitute material primarily for cylinders and other parts at a significant cost saving over cast or fabricated steel."

Materials Advantages

Castings offer advantages over forgings in isotropy of properties and over fabrications in both isotropy and homogeneity. The deformation processes used to produce forgings and plate for fabrications produce laminations which can result in a significant reduction in properties in a direction transverse to the lamination. In fabricated components, design complexity is usually achieved by the welding of plate or other wrought shapes. This method of construction can reduce component performance in two ways. First, material shape limitations often produce sharp corners which increase stress concentrations, and second, the point of shape change and stress concentration is often a weld, with related possibilities for material weakness and stress-raising defects. Figure 2.2 shows the results of stress analysis of an acrylic joint model in which the stress concentration factor for the weld is substantially higher than for a casting profiled to minimize stress concentration.

Cast Iron: The Natural Composite

Iron castings, as objects of art, weapons of war, or in more utilitarian forms, have been produced for more than 2000 years. As a commercial process, the production of iron castings probably has no equal for longevity, success or impact on our society. In a sense, the iron foundry industry produces an invisible yet vital product, since most iron castings are further processed, assembled, and then incorporated as components of other machinery, equipment, and consumer items.

The term "cast iron" refers not to a single material, but to a family of materials whose major constituent is iron, with important amounts of carbon and silicon, as shown in Figure 2.3. Cast irons are natural composite materials whose properties are determined by their microstruc-

Figure 2.4

Micrograph of Gray Iron showing crack-life behaviour of graphite flakes.

Figure 2.5

Micrograph of Ductile Iron showing how graphite spheroids can act as "crack-arresters".

tures – the stable and metastable phases formed during solidification or subsequent heat treatment. The major microstructural constituents of cast irons are: the chemical and morphological forms taken by carbon, and the continuous metal matrix in which the carbon and/or carbide are dispersed. The following important microstructural components are found in cast irons.

- **Graphite**

This is the stable form of pure carbon in cast iron. Its important physical properties are low density, low hardness and high thermal conductivity and lubricity. Graphite shape, which can range from flake to spherical, plays a significant role in determining the mechanical properties of cast irons. Figures 2.4 and 2.5 show that graphite flakes act like cracks in the iron matrix, while graphite spheroids act like "crack-arresters", giving the respective irons dramatically different mechanical properties.

- **Carbide**

Carbide, or cementite, is an extremely hard, brittle compound of carbon with either iron or strong carbide forming elements, such as chromium, vanadium or molybdenum. Massive carbides increase the wear resistance of cast iron, but make it brittle and very difficult to machine. Dispersed carbides in either lamellar or spherical forms play in important role in providing strength and wear resistance in as-cast pearlitic and heat-treated irons.

- **Ferrite**

This is the purest iron phase in a cast iron. In conventional Ductile Iron ferrite produces lower strength and hardness, but high ductility and toughness. In Austempered Ductile Iron (ADI), extremely fine-grained accicular ferrite provides an exceptional combination of high strength with good ductility and toughness.

- **Pearlite**

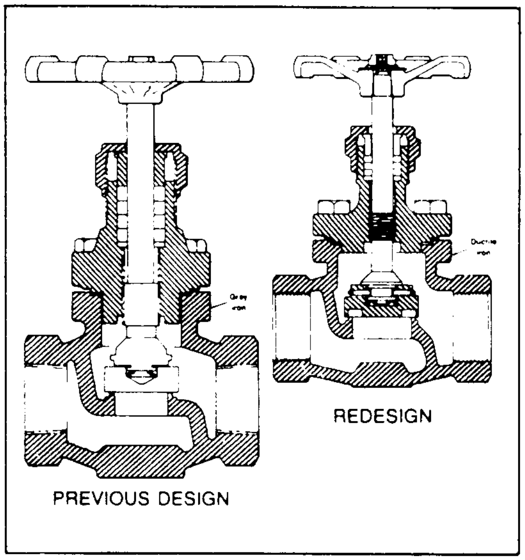
Pearlite, produced by a eutectoid reaction, is an intimate mixture of lamellar cementite in a matrix of ferrite. A common constituent of cast irons, pearlite provides a combination of higher strength and with a corresponding reduction in ductility which meets the requirements of many engineering applications.

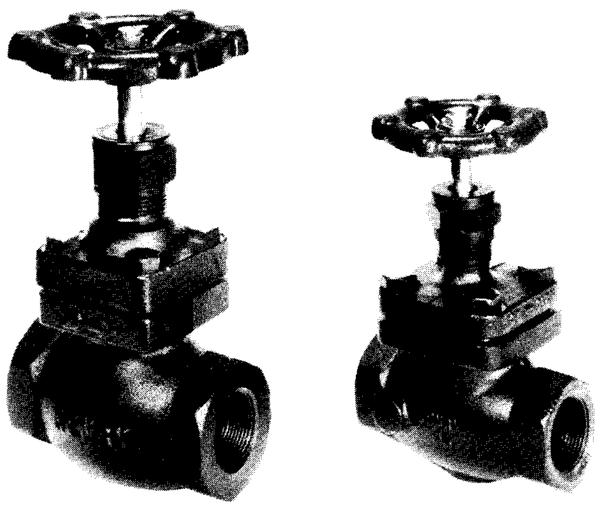
- **Martensite**

Martensite is a supersaturated solid solution of carbon in iron produced by rapid cooling. In the untempered condition it is very hard and brittle. Martensite is normally "tempered" – heat treated to reduce its carbon content by the precipitation of carbides – to provide a controlled combination of high strength and wear resistance.

- **Austenite**

Normally a high temperature phase consisting of carbon dissolved in iron, it can exist at room temperature in austenitic and austempered cast irons. In austenitic irons, austenite is stabilized by nickel in the range 18-36%. In austempered irons, austenite is produced by a combination of rapid cooling which suppresses the formation of pearlite, and the supersaturation of carbon during austempering, which depresses the start of the austenite-to-martensite transformation far below room





The need to redesign an ammonia valve line gave Henry Valve Co. of Illinois the opportunity to make the conversion from gray iron to Ductile Iron as shown. Size (thinner valve walls) and weight reductions (45% reduction) were achieved without sacrificing performance.

temperature. In austenitic irons, the austenite matrix provides ductility and toughness at all temperatures, corrosion resistance and good high temperature properties, especially under thermal cycling conditions. In austempered Ductile Iron stabilized austenite, in volume fractions up to 40% in lower strength grades, improves toughness and ductility and response to surface treatments such as fillet rolling.

- **Bainite**

Bainite is a mixture of ferrite and carbide, which is produced by alloying or heat treatment.

Types of Cast Irons

The presence of trace elements, the addition of alloying elements, the modification of solidification behaviour, and heat treatment after solidification are used to change the microstructure of cast iron to produce the desired mechanical properties in the following common types of cast iron.

White Iron

White Iron is fully carbidic in its final form. The presence of carbon in the form of different carbides, produced by alloying, makes White Irons extremely hard and abrasion resistant but very brittle.

Gray Iron

Gray Iron is by far the oldest and most common form of cast iron. As a result, it is assumed by many to be the only form of cast iron and the terms "cast iron" and "gray iron" are used interchangeably. Gray Iron, named because its fracture has a gray appearance, consists of carbon in the form of flake graphite in a matrix consisting of ferrite, pearlite or a mixture of the two. The fluidity of liquid gray iron, and its expansion during solidification due to the formation of graphite, have made this metal ideal for the economical production of shrinkage-free, intricate castings such as motor blocks.

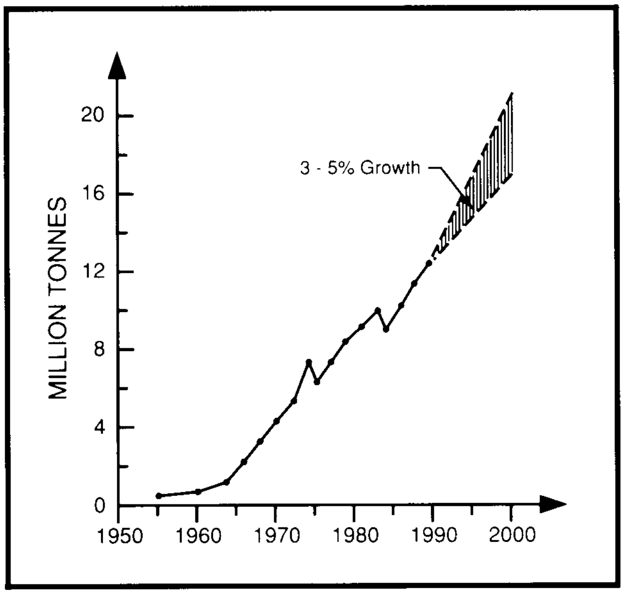
The flake-like shape of graphite in Gray Iron, see Figure 2.4, exerts a dominant influence on its mechanical properties. The graphite flakes act as stress raisers which may prematurely cause localized plastic flow at low stresses, and initiate fracture in the matrix at higher stresses. As a result, Gray Iron exhibits no elastic behaviour and fails in tension without significant plastic deformation. The presence of graphite flakes also gives Gray Iron excellent machinability, damping characteristics and self-lubricating properties.

Malleable Iron

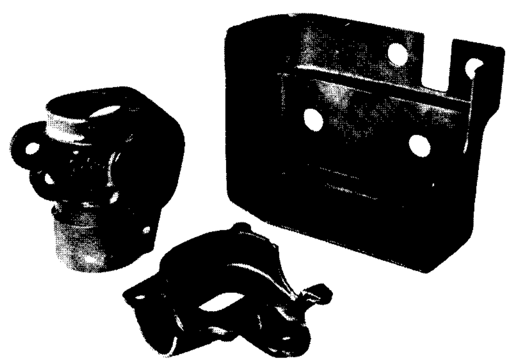
Unlike Gray and Ductile Iron, Malleable Iron is cast as a carbidic or white iron and an annealing or "malleablizing" heat treatment is required to convert the carbide into graphite. The microstructure of Malleable Iron consists of irregularly shaped nodules of graphite called "temper carbon" in a matrix of ferrite and/or pearlite. The presence of graphite in a more compact or sphere-like form gives Malleable Iron ductility and strength almost equal to cast, low-carbon steel. The formation of carbide during solidification results in the conventional shrinkage behaviour of Malleable Iron and the need for larger feed metal reservoirs, causing reduced casting yield and increased production costs.

SECTION II

Figure 2.6



Worldwide growth of Ductile Iron production, 1950-2000.



Courtesy: Metallgesellschaft, A. G. Germany

The scaffold fittings shown above, with 2 to 5 mm wall thickness, illustrate the excellent castability of Ductile Iron.

SECTION II

History of Ductile Iron Development

In spite of the progress achieved during the first half of this century in the development of Gray and Malleable Irons, foundrymen continued to search for the ideal cast iron – an as-cast "gray iron" with mechanical properties equal or superior to Malleable Iron. J.W. Bolton, speaking at the 1943 Convention of the American Foundrymen's Society (AFS), made the following statements.

"Your indulgence is requested to permit the posing of one question. Will real control of graphite shape be realized in gray iron? Visualize a material, possessing (as-cast) graphite flakes or groupings resembling those of malleable iron instead of elongated flakes."

A few weeks later, in the International Nickel Company Research Laboratory, Keith Dwight Millis made a ladle addition of magnesium (as a copper-magnesium alloy) to cast iron and justified Bolton's optimism – the solidified castings contained not flakes, but nearly perfect spheres of graphite. **Ductile Iron was born!**

Five years later, at the 1948 AFS Convention, Henton Morrogh of the British Cast Iron Research Association announced the successful production of spherical graphite in hypereutectic gray iron by the addition of small amounts of cerium.

At the time of Morrogh's presentation, the International Nickel Company revealed their development, starting with Millis' discovery in 1943, of magnesium as a graphite spherodizer. On October 25, 1949, patent 2,486,760 was granted to the International Nickel Company, assigned to Keith D. Millis, Albert P. Gegnebin and Norman B. Pilling. This was the official birth of Ductile Iron, and, as shown in Figure 2.6, the beginning of 40 years of continual growth worldwide, in spite of recessions and changes in materials technology and usage. What are the reasons for this growth rate, which is especially phenomenal, compared to other ferrous castings?

The Ductile Iron Advantage

The advantages of Ductile Iron which have led to its success are numerous, but they can be summarized easily – versatility, and higher performance at lower cost. As illustrated in Figure 2.7, other members of the ferrous casting family may have individual properties which might make them the material of choice in some applications, but none have the versatility of Ductile Iron, which often provides the designer with the best combination of overall properties. This versatility is especially evident in the area of mechanical properties where Ductile Iron offers the designer the option of choosing high ductility, with grades guaranteeing more than 18% elongation, or high strength, with tensile strengths exceeding 120 ksi (825 MPa). Austempered Ductile Iron (ADI), offers even greater mechanical properties and wear resistance, providing tensile strengths exceeding 230 ksi (1600 MPa).

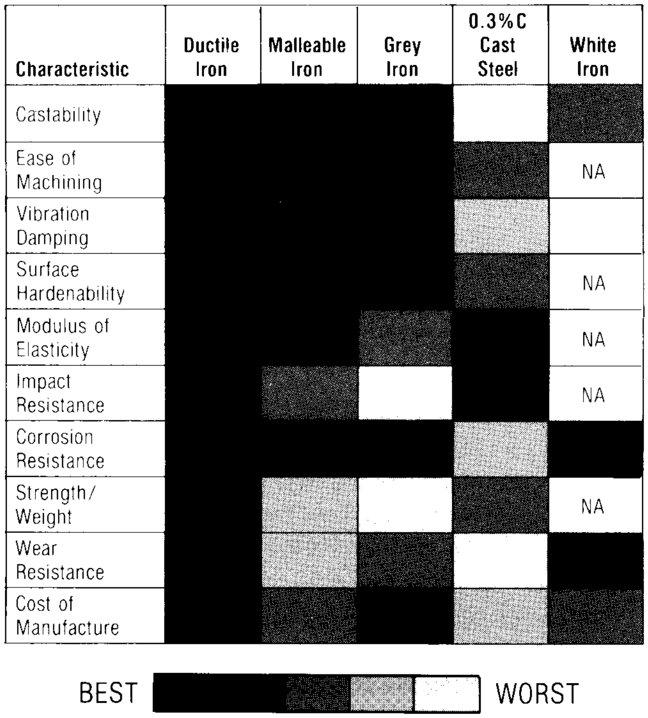
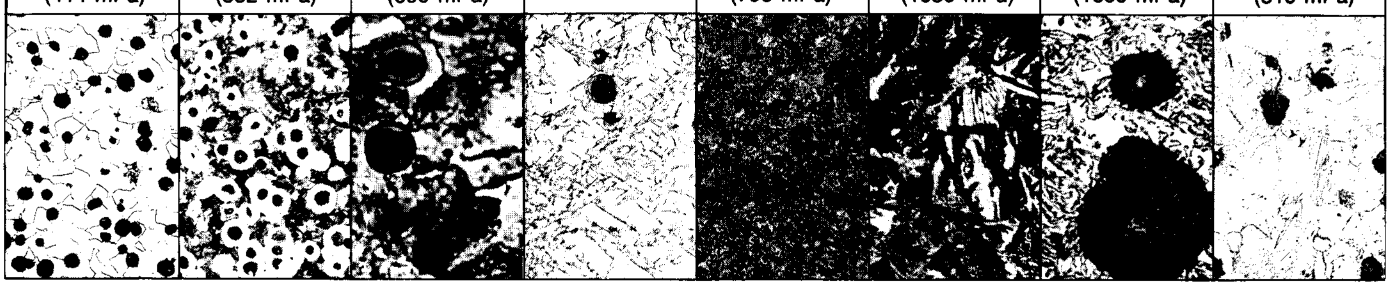


Figure 2.7

Comparison of the engineering characteristics of Ductile Iron versus competitive ferrous cast materials.

MATRIX							
Ferritic Grade 5	Ferritic-pearlitic Grade 3	Pearlitic Grade 1	Martensitic (With retained austenite)	Tempered Martensitic	ADI Grade 150	ADI Grade 230	Austenitic
60,000 p.s.i. (414 mPa)	80,000 p.s.i. (552 mPa)	100,000 p.s.i. (690 mPa)	N.A. *	115,000 p.s.i. (793 mPa)	150,000 p.s.i. (1050 mPa)	230,000 p.s.i. (1600 mPa)	45,000 p.s.i. (310 mPa)



* Approximate ultimate tensile strength 87,000 p.s.i.(600 mPa) Hard, Brittle.

(Note that the magnifications are different.)

Figure 2.8 **Microstructures and tensile strengths for various types of Ductile Iron.**

In addition to the cost advantages offered by all castings, Ductile Iron, when compared to steel and Malleable Iron Castings, also offers further cost savings. Like most commercial cast metals, steel and Malleable Iron decrease in volume during solidification, and as a result, require attached reservoirs (feeders or risers) of liquid metal to offset the shrinkage and prevent the formation of internal or external shrinkage defects. The formation of graphite during solidification causes an internal expansion of Ductile Iron as it solidifies and as a result, it may be cast free of significant shrinkage defects either with feeders that are much smaller than those used for Malleable Iron and steel or, in the case of large castings produced in rigid molds, without the use of feeders. The reduction or elimination of feeders can only be obtained in correctly design castings. This reduced requirement for feed metal increases the productivity of Ductile Iron and reduces its material and energy requirements, resulting in substantial cost savings. The use of the most common grades of Ductile Iron "as-cast" eliminates heat treatment costs, offering a further advantage.

The Ductile Iron Family

Ductile Iron is not a single material, but a family of materials offering a wide range of properties obtained through microstructure control. The common feature that all Ductile Iron share is the roughly spherical shape of the graphite nodules. As shown in Figure 2.5, these nodules act as "crack-arresters" and make Ductile Iron "ductile". This feature is essential to the quality and consistency of Ductile Iron, and is measured and controlled with a high degree of assurance by competent Ductile Iron foundries. With a high percentage of graphite nodules present in the structure, mechanical properties are determined by the Ductile Iron matrix. Figure 2.8 shows the relationship between microstructure and tensile strength over a wide range of properties. The importance of matrix in controlling mechanical properties is emphasized by the use of matrix names to designate the following types of Ductile Iron.

Ferritic Ductile Iron

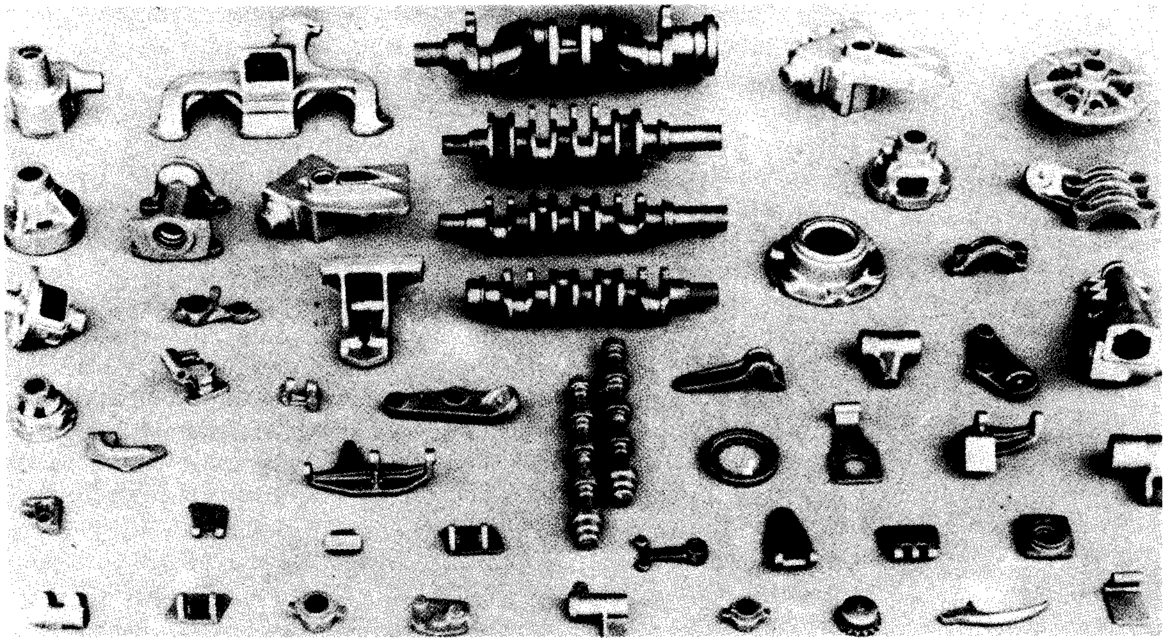
Graphite spheroids in a matrix of ferrite provides an iron with good ductility and impact resistance and with a tensile and yield strength equivalent to a low carbon steel. Ferritic Ductile Iron can be produced "as-cast" but may be given an annealing heat treatment to assure maximum ductility and low temperature thoughness.

Ferritic-Pearlitic Ductile Iron

These are the most common grades of Ductile Iron and are normally produced in the "as cast" condition. The graphite spheroids are in a matrix containing both ferrite and pearlite. Properties are intermediate between ferritic and pearlitic grades, with good machinability and low production costs.

Pearlitic Ductile Iron

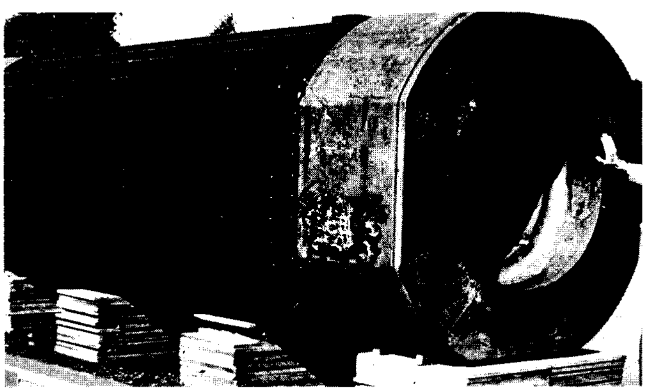
Graphite spheroids in a matrix of pearlite result in an iron with high strength, good wear resistance, and moderate ductility and impact resistance. Machinability is also superior to steels of comparable physical properties.



Courtesy: Toyota Motor Corporation

Figure 2.9 **Examples of typical Ductile Iron castings used in a modern automobile.**

Figure 2.10



Ductile Iron nuclear waste container weighing 85 tons.

Courtesy: Siempelkamp, Krefeld, Federal Republic of Germany

The preceding three types of Ductile Iron are the most common and are usually used in the as-cast condition, but Ductile Iron can be also be alloyed and/or heat treated to provide the following grades for a wide variety of additional applications.

Martensitic Ductile Iron

Using sufficient alloy additions to prevent pearlite formation, and a quench-and-temper heat treatment produces this type of Ductile Iron. The resultant tempered martensite matrix develops very high strength and wear resistance but with lower levels of ductility and toughness.

Bainitic Ductile Iron

This grade can be obtained through alloying and/or heat treatment to produce a hard, wear resistant material.

Austenitic Ductile Iron

Alloyed to produce an austenitic matrix, this Ductile Iron offers good corrosion and oxidation resistance, good magnetic properties, and good strength and dimensional stability at elevated temperatures. The unique properties of Austenitic Ductile Irons are treated in detail in Section V.

Austempered Ductile Iron (ADI)

ADI, the most recent addition to the Ductile Iron family, is a sub-group of Ductile Irons produced by giving conventional Ductile Iron a special austempering heat treatment. Nearly twice as strong as pearlitic Ductile Iron, ADI still retains high elongation and toughness. This combination provides a material with superior wear resistance and fatigue strength. (See Section IV).

A Matter of Confidence

The automotive industry has expressed its confidence in Ductile Iron through the extensive use of this material in safety related components such as steering knuckles and brake calipers. These and other automotive applications, many of which are used "as-cast", are shown in Figure 2.9. One of the most critical materials applications in the world is in containers for the storage and transportation of nuclear wastes. The Ductile Iron nuclear waste container shown in Figure 2.10 is another example of the ability of Ductile Iron to meet and surpass even the most critical qualification tests for materials performance. These figures show the wide variety of parts produced in Ductile Iron. The weight range of possible castings can be from less than one ounce (28 grams) to more than 200 tons. Section size can be as small as 2 mm to more than 20 inches (1/2 meter) in thickness.

The use of **Sorelmetal** for the production of Ductile Iron is recommended so that the maximum properties can be obtained in the casting.

SECTION II

REFERENCES

S. Jeffreys, "Finite Element Analysis - Doing Away with Prototypes", Industrial Computing, September, 1988, pp 34-36.

"NCMS Study Reveals DI Castings May Mean Cost Savings." Modern Casting, May, 1990, p 12.

Jay Janowak, "The Grid Method of Cast Iron Selection", Casting Design and Application, Winter 1990, pp 55-59.

D. P. Kanicki, "Marketing of Ductile Iron," Modern Casting, April, 1988.

A Design Engineer's Digest of Ductile Iron, 5th Edition, 1983, QIT-Fer et Titane Inc., Montreal, Quebec, Canada.

S. I. Karsay, Ductile Iron II, Quebec Iron and Titanium Corporation, 1972.

B. L. Simpson, History of the Metalcasting Industry, American Foundrymen's Society, Des Plaines, IL, 1969.

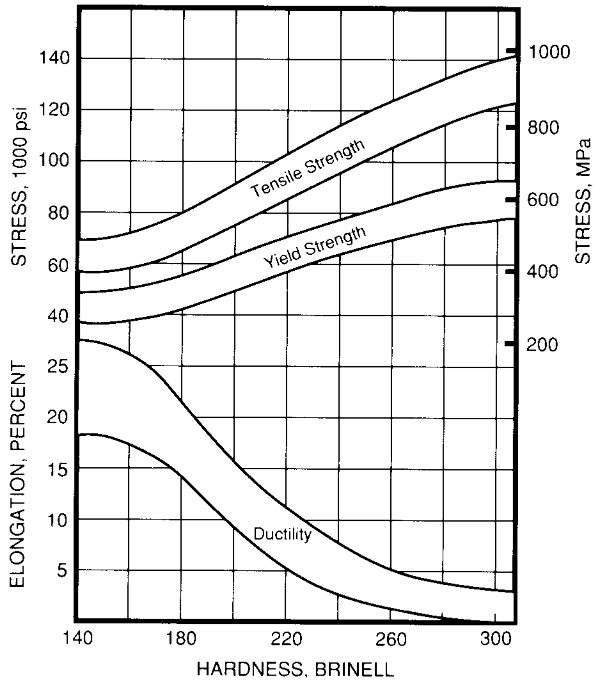
H. Bornstein, "Progress in Iron Castings", The Charles Edgar Hoyt Lecture, Transactions of the American Foundrymen's Society, 1957, vol 65, p 7.

G.J. Marston "Better cast than fabricated", The Foundryman, March 1990, 108-113.

SECTION III

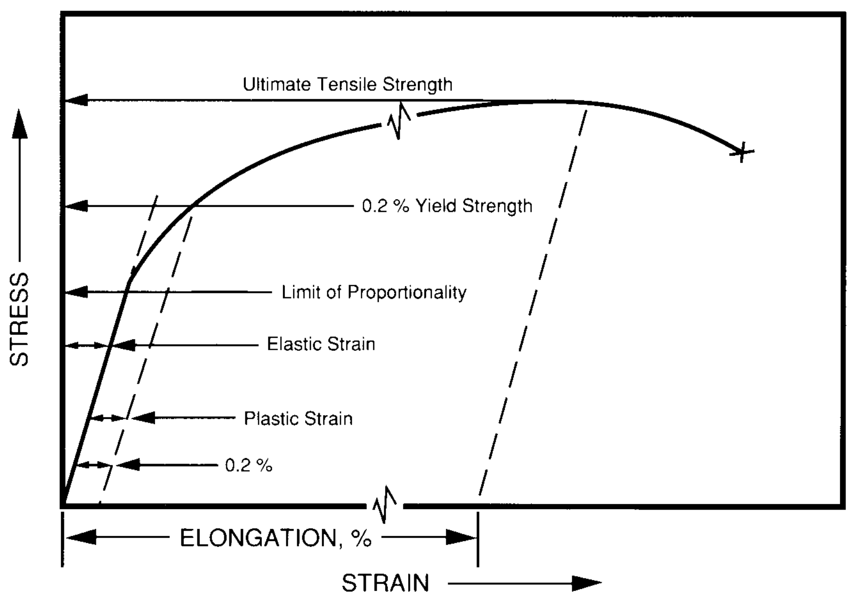
ENGINEERING DATA

Figure 3.1



General relationships between tensile properties and hardness for Ductile Iron.

Figure 3.2



Typical stress-strain curve for Ductile metals.

SECTION III

ENGINEERING DATA

Introduction

Ductile Iron is not a single material, but a family of versatile cast irons exhibiting a wide range of properties which are obtained through microstructure control. The most important and distinguishing microstructural feature of all Ductile Irons is the presence of graphite nodules which act as "crack-arresters" and give Ductile Iron ductility and toughness superior to all other cast irons, and equal to many cast and forged steels. As shown in Figure 2.8, Section II, the matrix in which the graphite nodules are dispersed plays a significant role in determining mechanical properties.

Matrix control, obtained in conventional Ductile Iron either "as-cast" through a combination of composition and process control, or through heat treatment, gives the designer the option of selecting the grade of Ductile Iron which provides the most suitable combination of properties. Figure 3.1 illustrates the wide range of strength, ductility and hardness offered by conventional Ductile Iron. The high ductility ferritic irons shown on the left provide elongation in the range 18-30 per cent, with tensile strengths equivalent to those found in low carbon steel. Pearlitic Ductile Irons, shown on the right side, have tensile strengths exceeding 120 ksi (825 MPa) but reduced ductility. Austempered Ductile Iron (ADI), discussed in Section IV, offers even greater mechanical properties and wear resistance, with ASTM Grades providing tensile strengths exceeding 230 ksi (1600 MPa). Special Alloy Ductile Irons, described in Section V, can be selected to provide creep and oxidation resistance at high temperatures, resistance to thermal cycling, corrosion resistance, special magnetic properties, or low temperature toughness.

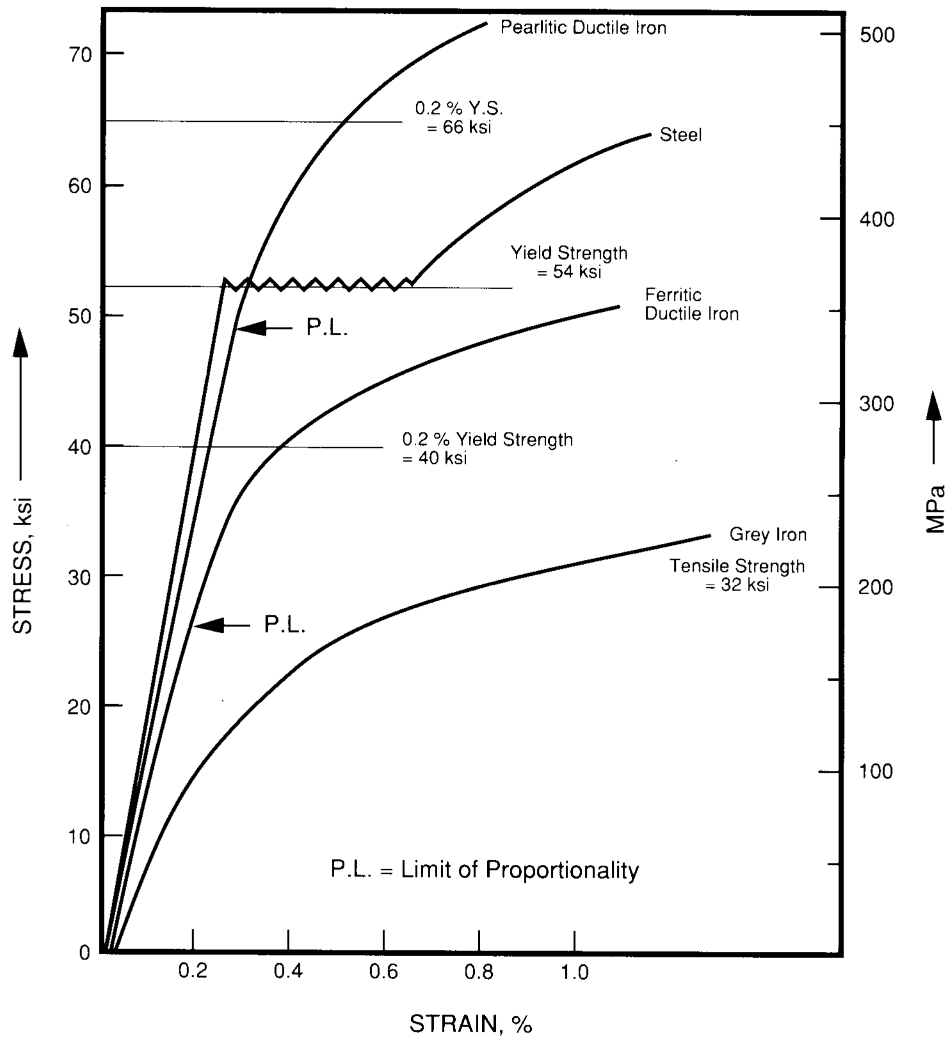
The numerous, successful uses of Ductile Iron in critical components in all sectors of industry highlight its versatility and suggest many additional applications. In order to use Ductile Iron with confidence, the design engineer must have access to engineering data describing the following mechanical properties: elastic behaviour, strength, ductility, hardness, fracture toughness and fatigue properties. Physical properties – thermal expansion, thermal conductivity, heat capacity, density, and magnetic and electrical properties – are also of interest in many applications. This Section describes the mechanical and physical properties of conventional Ductile Irons, relates them to microstructure, and indicates how composition and other production parameters affect properties through their influence on microstructure.

TENSILE PROPERTIES

The tensile properties of conventional Ductile Iron, especially the yield and tensile strenghts and elongation, have traditionally been the most widely quoted and applied determinants of mechanical behaviour. Most of the worldwide specifications for Ductile Iron summarized in Section XII describe properties of the different grades of Ductile Iron

SECTION III

Figure 3.3



Elastic and yielding behavior for steel, Gray Iron and ferritic and pearlitic Ductile Irons.

primarily by their respective yield and tensile strengths and elongation. Hardness values, usually offered as additional information, and impact properties, specified only for certain ferritic grades, complete most specifications. Although not specified, the modulus of elasticity and proportional limit are also vital design criteria. Figure 3.2 illustrates a generalized engineering stress-strain curve describing the tensile properties of ductile engineering materials.

Modulus of Elasticity

Figure 3.2 shows that, at low tensile stresses, there is a linear or proportional relationship between stress and strain. This relationship is known as Hooke's Law and the slope of the straight line is called the Modulus of Elasticity or Young's Modulus. As shown in Figure 3.3, the initial stress-strain behaviour of Ductile Iron lies between those of mild steel and Gray Iron. Annealed or normalized mild steels exhibit elastic behaviour until the yield point, where plastic deformation occurs suddenly and without any initial increase in flow stress. In Gray Iron, the graphite flakes act as stress-raisers, initiating microplastic deformation at flake tips at very low applied stresses. This plastic deformation causes the slope of the stress-strain curve to decrease continually and as a result Gray Iron does not exhibit true elastic behaviour.

Ductile Iron exhibits a proportional or elastic stress-strain relationship similar to that of steel, but which is limited by the gradual onset of plastic deformation. The Modulus of Elasticity for Ductile Iron, measured in tension, varies from 23.5 to 24.5 x 10^6 psi (162 – 170 GPa). In cantilever, three point beam or torsion testing, values as low as 20.5 x 10^6 have been reported. The Dynamic Elastic Modulus (DEM), the high frequency limit of the Modulus of Elasticity measured by the resonant frequency test, exhibits a range of 23.5 to 27 x 10^6 psi (162 – 186 GPa).

Poisson's Ratio

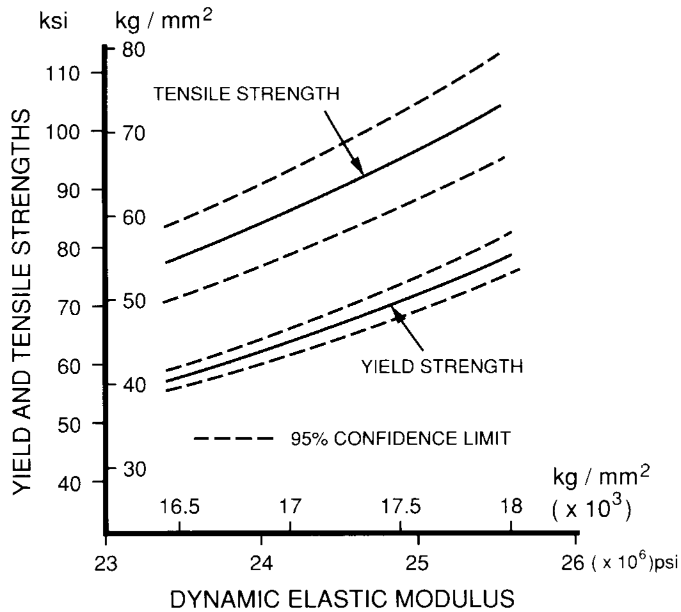
Poisson's Ratio, the ratio of lateral elastic strain to longitudinal elastic strain produced during a tensile test, shows little variation in Ductile Iron. A commonly accepted value is 0.275.

Proportional Limit

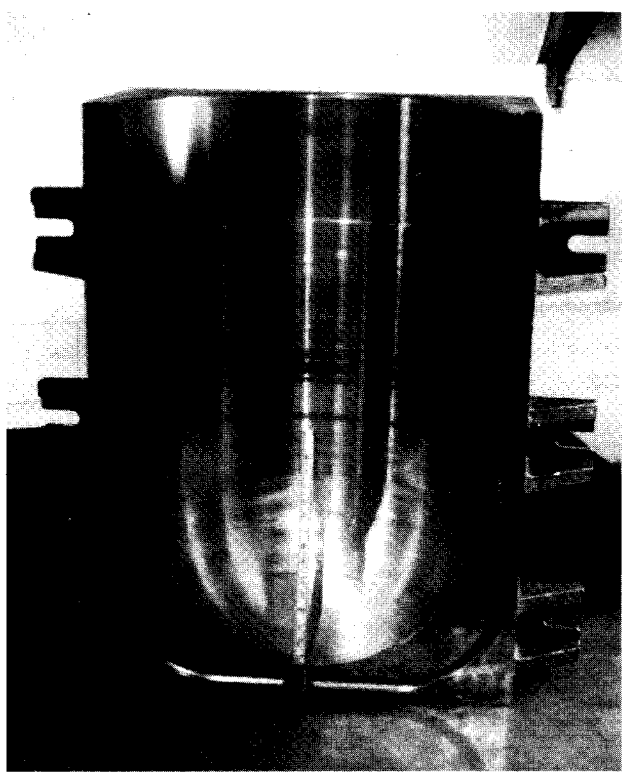
The proportional limit (also called the limit of proportionality) is the maximum stress at which a material exhibits elastic behaviour. When a material is stressed below the limit of proportionality, and the stress is then removed, the stress-strain curve returns to the origin – no permanent change in dimension occurs. When the stress exceeds the proportional limit, plastic strain reduces the slope of the stress-strain curve. Upon removal of the stress, the strain decreases linearly, following a line parallel to the original elastic curve. At zero stress, the strain does not return to zero, exhibiting a permanent plastic strain, or change in dimension of the specimen (see Figure 3.2).

In Ductile Irons, which exhibit a gradual transition from elastic to plastic behaviour, the proportional limit is defined as the stress required to

Figure 3.4



Relationships between yield and tensile strengths and dynamic elastic modulus for Ductile Iron.



Machined Ductile Iron slag pot half (subsequently austempered acier machining).

produce a deviation from elastic behaviour of 0.005%. It is measured by the offset method used to measure the yield strength and may also be estimated from the yield strength. The ratio of proportional limit to 0.2% yield strength is typically 0.71 for ferritic grades, decreasing to 0.56 for pearlitic and tempered martensitic grades.

Yield Strength

The yield strength, or proof stress is the stress at which a material begins to exhibit significant plastic deformation. The sharp transition from elastic to plastic behaviour exhibited by annealed and normalized steels (Figure 3.3) gives a simple and unambiguous definition of yield strength. For Ductile Iron the offset method is used in which the yield strength is measured at a specified deviation from the linear relationship between stress and strain. This deviation, usually 0.2%, is included in the definition of yield strength or proof stress in international specifications (see Section XII) and is often incorporated in the yield strength terminology, e.g. "0.2% yield strength". Yield strengths for Ductile Iron typically range from 40,000 psi (275 MPa) for ferritic grades to over 90,000 psi (620 MPa) for martensitic grades.

Tensile Strength

The tensile strength, or ultimate tensile strength (UTS), is the maximum load in tension which a material will withstand prior to fracture. It is calculated by dividing the maximum load applied during the tensile test by the original cross sectional area of the sample. Tensile strengths for conventional Ductile Irons generally range from 60,000 psi (414 MPa) for ferritic grades to over 200,000 psi (1380 MPa) for martensitic grades.

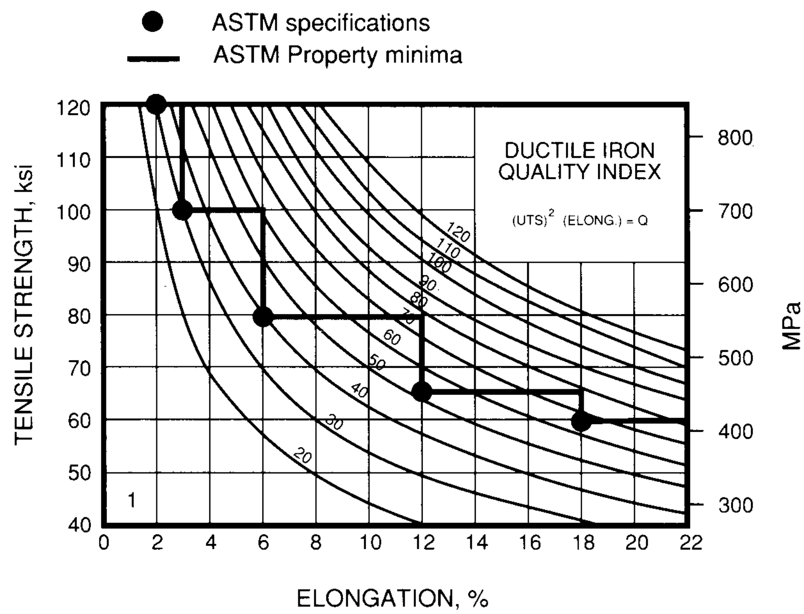
Elongation

Elongation is defined as the permanent increase in length, expressed as a percentage of a specified gage length marked in a tensile test bar, which is produced when the bar is tested to failure. Elongation is used widely as the primary indication of tensile ductility and is included in many Ductile Iron specifications. Although shown as the uniform elongation in Figure 3.2, elongation also includes the localized deformation that occurs prior to fracture. However, because the localized deformation occurs in a very limited part of the gage length, its contribution to the total elongation of a correctly proportioned bar is very small. Brittle materials such as Gray Iron can fail in tension without any significant elongation, but ferritic Ductile Irons can exhibit elongation of over 25%. Austempered Ductile Irons exhibit the best combination of strength and elongation (See Section IV).

Relationships between Tensile Properties

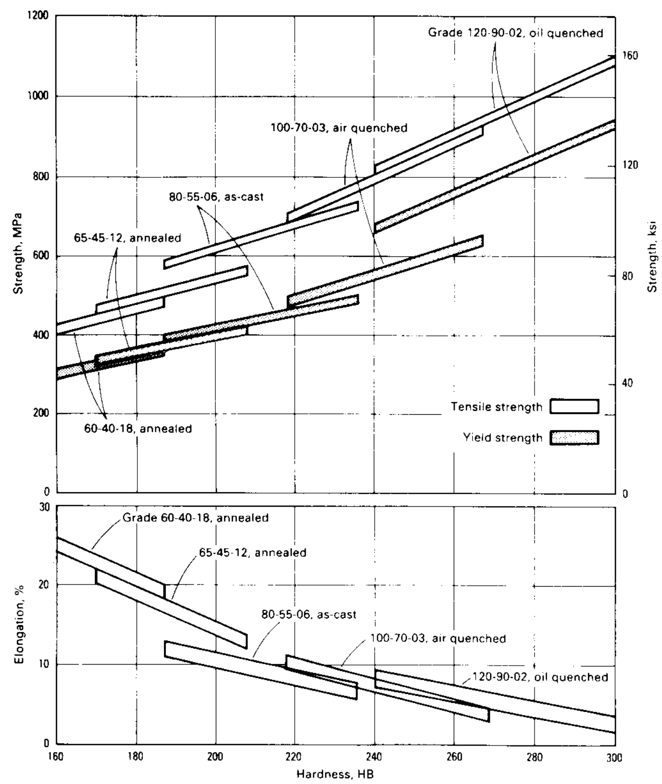
The strong influence of graphite morphology and matrix structure on the different tensile properties of Ductile Iron produces significant correlations between these properties. Figure 3.4 illustrates the non-linear least square relationships between tensile and yield strengths and the dynamic elastic modulus.

Figure 3.5



Relationship between Quality Index for Ductile Iron and ASTM Specification A536.

Figure 3.6



Tensile and hardness properties of Ductile Iron conforming to different grades of ASTM Specification A536.

SECTION III

In 1970 Siefer and Orths, in a statistical study of the mechanical properties of a large number of Ductile Iron samples, identified a relationship between tensile strength and elongation of the form:

$$(\text{tensile strength ksi})^2 \times (\text{elongation } \%) \div 1000 = Q$$

where Q is a constant.

A larger value of Q indicates a combination of higher strength and elongation and, therefore, higher material performance. Crews (1974) defined Q as the Quality Index (QI) for Ductile Iron. Both the QI and the underlying relationship between strength and elongation offer valuable insights into the quality of different Ductile Iron castings and the feasibility of obtaining various combinations of properties. High QI values have been shown to result from high nodularity (high percentage of spherical or near-spherical graphite particles), absence of intercellular degenerate graphite, high nodule count, a low volume fraction of carbides, low phosphorus content (<0.03%) and freedom from internal porosity. High quality castings with these characteristics can be produced consistently by a competent, modern Ductile Iron foundry.

SECTION III

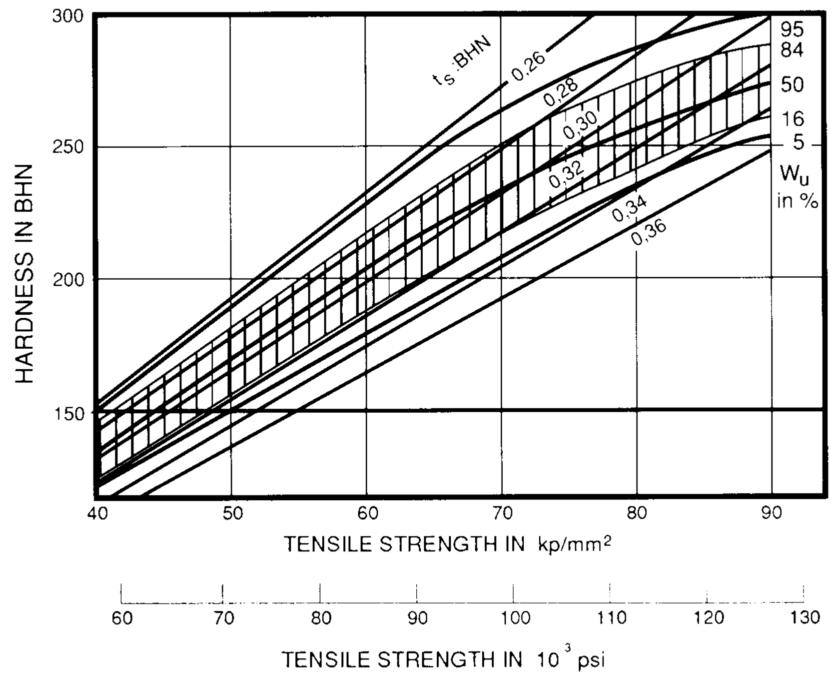
Figure 3.5 illustrates the tensile strength-elongation relationships for different QI levels of Ductile Iron. Each curve is an "iso-quality" line along which strength-elongation values can be displaced by annealing or normalizing heat treatments which change the matrix ferrite: pearlite ratio. Quench-and-temper heat treatments produce curves which are similar but displaced slightly toward higher quality. This iso-quality concept can assist in the arbitration of irons which are of sufficient quality but are off-grade by virtue of their position in Figure 3.5 relative to the ASTM grade limits. For example, 3 different irons, all with a QI of 70, could have strength-elongation values of 64 ksi/17.1%, 70 ksi/14.3% and 78 ksi/11.5%. Although only the 70 ksi iron meets the 65-45-12 grade requirement, the other two irons, on the basis of identical QI, might be judged equally fit for the intended purpose.

The following comparison of QI values reveals the impact of 20 years of progress in Ductile Iron production technology and quality control.

Siefer and Orths (1970)		Venugopalan & Alagarsamy (1990)	
$Q_{99.5}$ (metric)	= 60,000	Q_{max} (metric)	= 64,500
$Q_{99.5}$ (Imperial)	= 120,000	Q_{max} (Imperial)	= 129,000
Q_{50} (metric)	= 30,000	Q_{50} (metric)	= 45,000
Q_{50} (Imperial)	= 60,000	Q_{50} (Imperial)	= 90,000

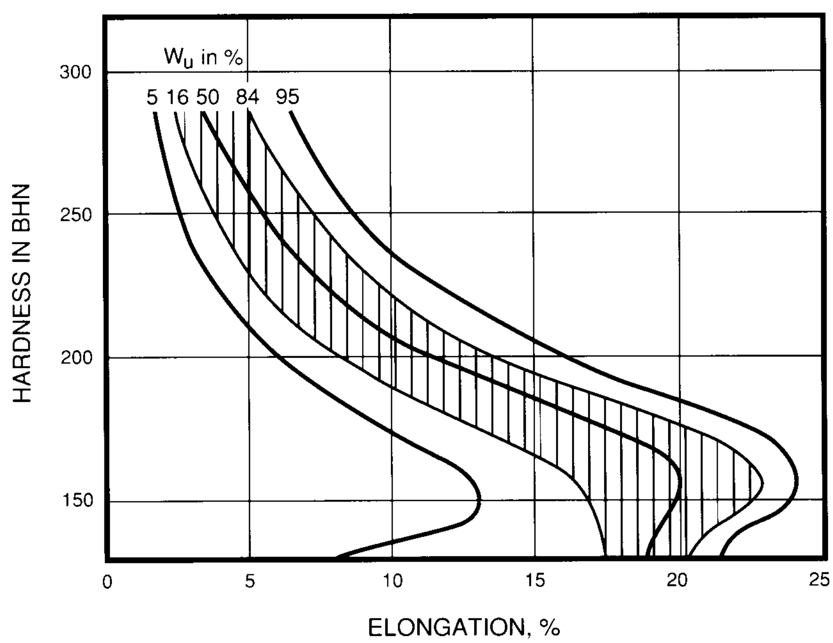
where: tensile strength (metric) is expressed in kp/mm^2,
tensile strength (Imperial) is expressed in ksi,
$Q_{99.5}$ and Q_{50} indicate the quality levels exceeded by 0.5% and

Figure 3.7



Relationship between tensile strength and hardness of Ductile Iron. Wu indicates per cent of sample exceeding indicated tensile strength for a constant hardness (1 kp/mm^2 = 9.807 MPa).

Figure 3.8



Relationship between elongation and hardness of Ductile Iron. Wu indicates % of sample with elongation less than indicated value for constant hardness.

SECTION III

50% respectively of the samples tested, and
Q_{max} is the maximum quality exhibited by a batch of 34 samples of commercial Ductile Iron (Figure 3.9).

As might be expected from two decades of progress in Ductile Iron production technology and process control, the maximum QI increased by 7.5% but the median QI increased by 50%, **indicating a significant improvement in consistency** of properties. The application of the Quality Index concept to Austempered Ductile Iron highlights the superior combination of strength and elongations offered by this material, with ASTM A897-90 Grades 125/80/10 and 150/100/7 having minimum Quality Indices of 156 and 158 respectively.

The inverse relationship between tensile strength and elongation is followed by all Ductile Iron specifications (see Section XII), as shown in Figure 3.6 for ASTM specification A536-80. The various grade specifications shown in Figure 3.6 and their minimum property boundaries are superimposed on the Siefer and Orths diagram (Figure 3.5) in order to indicate the relative qualities of irons required to meet the different grades. Examination of Figure 3.5 reveals several relationships between the ASTM grades and Ductile Iron Quality Indices.

SECTION III

- The Grade 60-40-18 has the highest Quality Index, 64.8, with the Quality Index decreasing to a value of 29 for Grade 120-90-02.

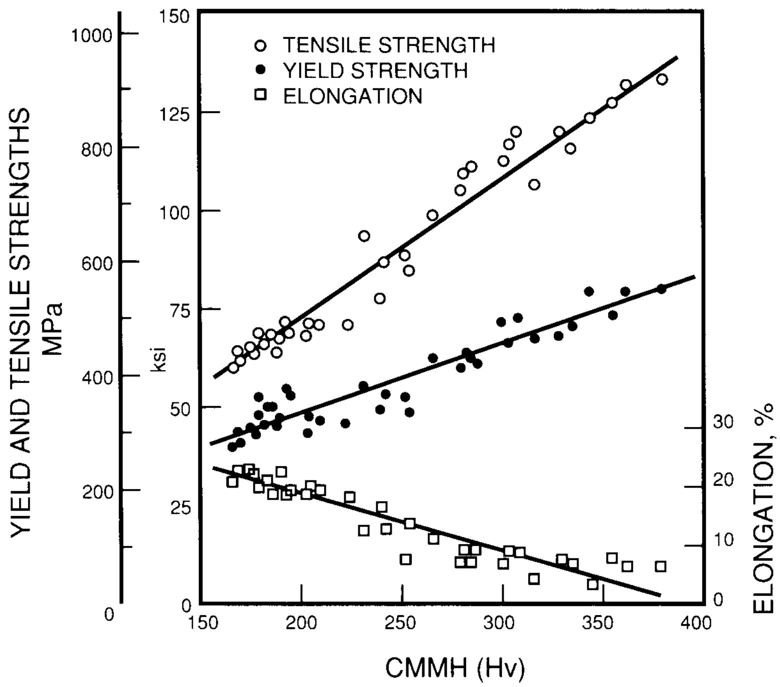
- The properties corresponding to a grade designation e.g. 65-45-12, define the minimum Quality Index – 50.7 – required to meet that grade. The property boundaries for that grade define Quality Index levels which increase until the boundary of the next grade is reached – 76.8 for the boundary with 80-55-06 and 76 for the boundary with 60-40-18.

- The mean Quality Index Q_{50} for the data of Venugopalan and Alagarsamy – 90 – is substantially higher than the Quality Indices required to meet all requirements for ASTM A536-80.

Hardness

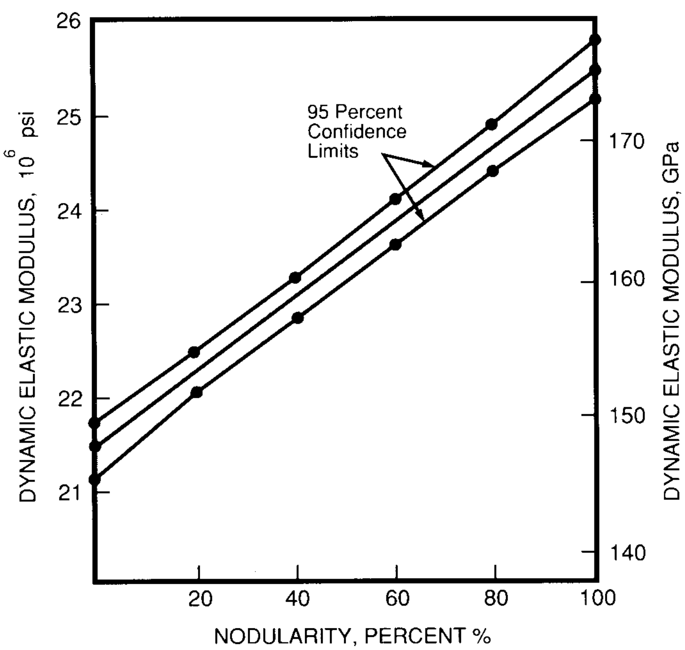
The hardness of Ductile Iron is usually and best measured by the Brinell test, in which a 10 mm diameter hardened steel or tungsten carbide ball is pressed into a flat surface of the workpiece. Hardness is expressed as a Brinell Indentation Diameter (BID) or a Brinell Hardness Number (BHN). Hardness may also be described as BHN/3000 to indicate the force applied to the ball is 3000 kg, the normal value for ferrous materials. The size of the Brinell indentation, and its related volume of plastic deformation, are large relative to the scale of the microstructure and as a result an average hardness is obtained which exhibits good reproducibility for similar microstructures.

Figure 3.9



Relationships between actual tensile properties and properties calculated from CMMH values.

Figure 3.10



Relationship between Dynamic Elastic Modulus (DEM) and nodularity.

SECTION III

Brinell Hardness is included in many Ductile Iron specifications. Brinell Hardness should be used for production control and as an auxiliary property test, for example to control machinability. Microhardness testing, using either the Knoop or Vickers indenters, can be used to measure the hardness of the individual components of the Ductile Iron matrix.

Tensile Properties vs Hardness.

Figures 3.7 and 3.8 illustrate the relationships between Brinell Hardness, tensile strength and elongation respectively. Figure 3.7 indicates that 90% of all castings with a hardness of 150 BHN will have tensile strengths between 40 and 50 kp/mm^2 (57-71 ksi), while the equivalent range of strength corresponding to a hardness of 250 BHN would be 66-87 kp/mm^2 (94-124 ksi). Figure 3.8 reveals a more complex relationship between BHN and elongation. For a hardness of 150 BHN, 90% of the castings would have elongation in the range 13-24%. At 250 BHN the equivalent range is 2.5 to 8.5%. Because of the magnitude of these variations, Brinell Hardness alone should not be used to determine tensile properties, especially elongation.

SECTION III

Microhardness data for the individual microstructural components can be used to predict the tensile properties of as-cast, annealed, and normalized commercial Ductile Iron. Figure 3.9, from Venugopalan and Alagarsamy, compares strength and elongation data with the following linear progression curves:

tensile strength (ksi) = 0.10 + 0.36 x CMMH
yield strength (ksi) = 12 + 0.18 x CMMH
elongation (%) = 37.85 – 0.093 x CMMH.

CMMH is composite matrix microhardness, and is defined as:

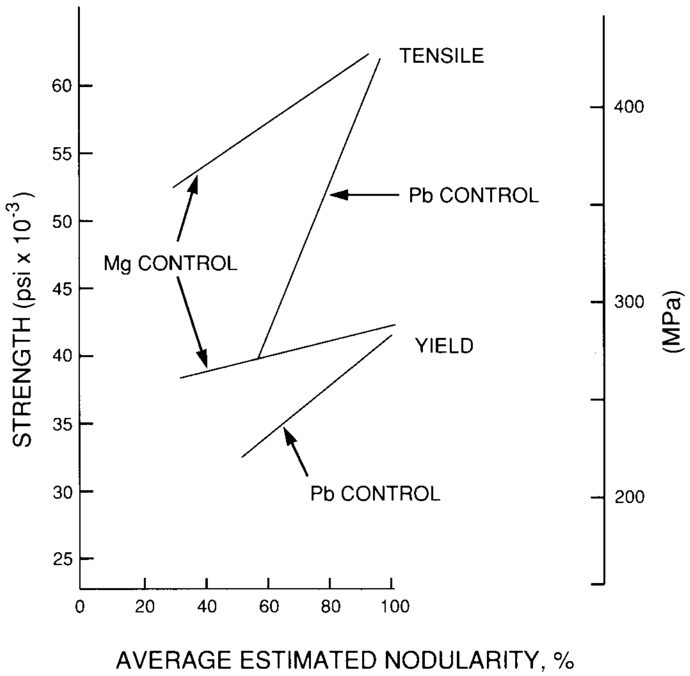
CMMH = ((HF x%F) + (HP x%P))/100,

where HF and%F, and HP and%P are the respective hardnesses and volume fractions of ferrite and pearlite.

Effect of Graphite Shape

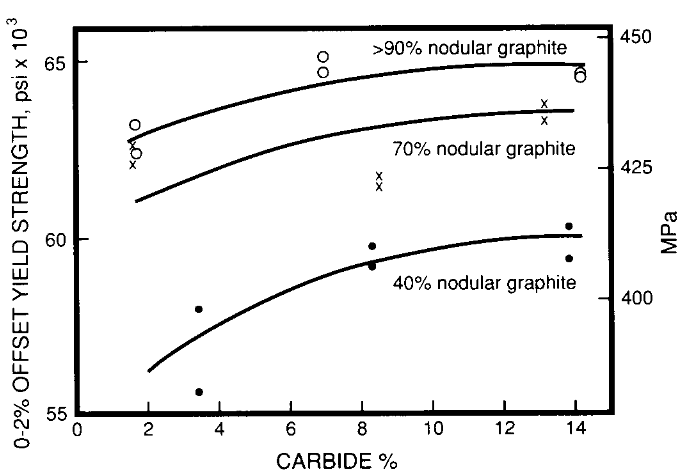
As would be expected from the dramatic differences in mechanical properties between Gray and Ductile Iron, that nodularity plays a significant role in determining properties within the Ductile Iron family. Figure 3.10 illustrates the correlation between nodularity and Dynamic Elastic Modulus. This relationship not only emphasizes the strong influence of nodularity on DEM, but also indicates that DEM values obtained by sonic testing can be used to measure nodularity (graphite volume and nodule count should be relatively constant).

Figure 3.11



Effect of Mg-controlled and Pb-controlled nodularity on yield and tensile strengths of ferritic Ductile Iron.

Figure 3.12



Effect of nodularity and carbide content on yield strength of pearlitic Ductile Iron.

SECTION III

Nodularity, and the morphology of the non-spherical particles produced as nodularity decreases, exert a strong influence on the yield and tensile strengths of Ductile Iron. Figure 3.11 shows the relationships between strength and nodularity for ferritic irons in which nodularity has been changed by two methods: through magnesium control, or through lead control. When nodularity is decreased by reducing the amount of residual magnesium (the most common spheroidizing agent used in commercial Ductile Iron) the nodules become elongated, but do not become sharp or "spiky". The result is a 10% decrease in yield strength and a 15% decrease in tensile strength when nodularity is reduced to 30%. Small additions of lead reduce nodularity by producing intergranular networks of "spiky" or plate-like graphite which result in dramatic reductions in tensile properties.

SECTION III

The effect of nodularity on pearlitic Ductile Irons can be determined in Figures 3.12 and 3.13 by comparing the tensile properties, at constant carbide levels, of irons with nodularities of 90, 70 and 40%. These Figures reveal two important features. First, compared to the Mg-controlled loss of nodularity for the ferritic iron in Figure 3.11, the pearlitic iron is much more sensitive to reduced nodularity. Second, at low carbide levels typical of good quality Ductile Iron, there is relatively little loss of strength as the nodularity decreases to 70% but as nodularity deteriorates further, strength decreases more rapidly.

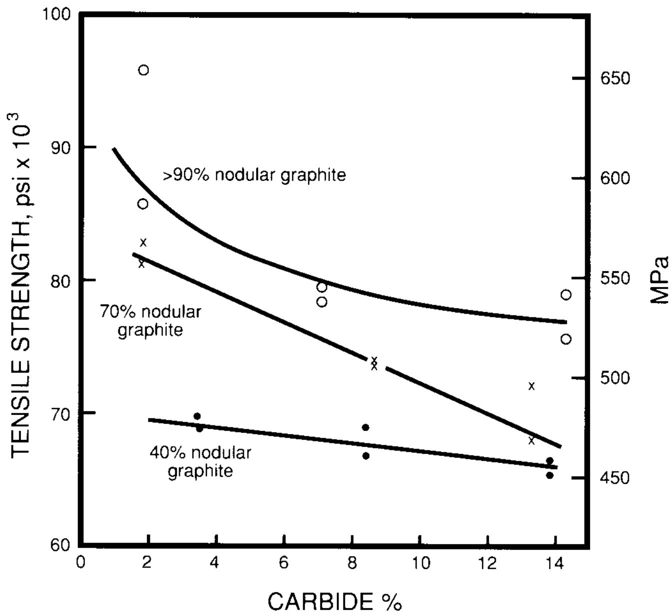
Although not shown in Figures 3.11-13, the effect of nodularity on elongation can be inferred by considering the influence of nodularity on the **difference** between the yield and tensile strengths, which is proportional to elongation. Both Mg- and Pb-controlled losses in nodularity reduce the difference between the yield and tensile stresses, indicating that loss of nodularity results in reduced elongation. The dramatic decrease in tensile strength produced by lead control indicates that the formation of spiky, intercellular graphite can severely embrittle Ductile Iron.

Designers can virtually eliminate the effect of nodularity on tensile properties by specifying that the nodularity should exceed 80-85% and that there should be no intercellular flake graphite. These criteria can be met easily by good production practices which ensure good nodularity through Mg control and prevent flake or spiky graphite by a combination of controlling flake-producing elements and eliminating their effects through the use of small additions of cerium.

Effect of Nodule Count

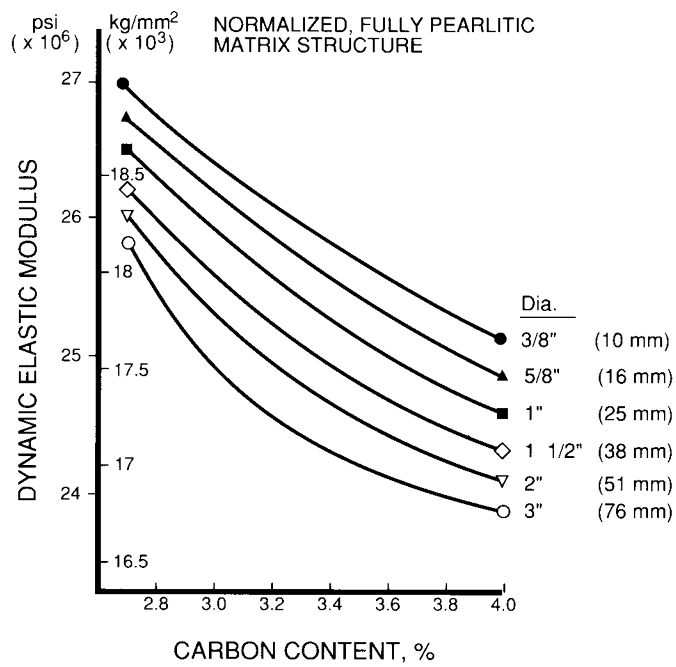
Nodule Count, expressed as the number of graphite nodules/mm^2, also influences the mechanical properties of Ductile Iron, although not as

Figure 3.13



Effect of nodularity and carbide content on tensile strength of pearlitic Ductile Iron.

Figure 3.14



Effect of carbon content and casting diameter on the dynamic elastic modulus of fully pearlitic Ductile Iron.

strongly and directly as graphite shape. Generally, high nodule count indicates good metallurgical quality, but there is an optimum range of nodule count for each section size of casting, and nodule counts in excess of this range may result in a degradation of properties. Nodule count per se does not strongly affect tensile properties, but it has the following effects on microstructure, which can significantly influence properties.

- Nodule count influences the pearlite content of as-cast Ductile Iron. Increasing the nodule count decreases the pearlite content, decreasing strength and increasing elongation.

- Nodule count affects carbide content. Increasing the nodule count improves tensile strength, ductility and machinability by reducing the volume fractions of chill carbides, segregation carbides, and carbides associated with "inverse chill".

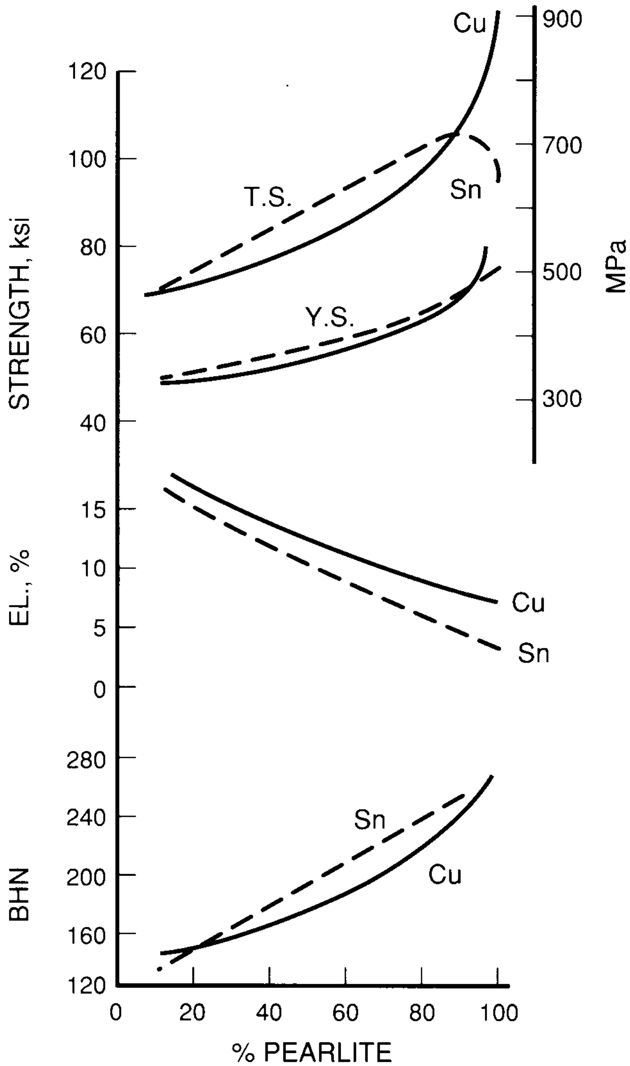
- Matrix homogeneity is influenced by nodule count. Increasing the nodule count produces a finer and more homogeneous microstructure. This refinement of the matrix structure reduces the segregation of harmful elements which might produce intercellular carbides, pearlite or degenerate graphite.

- Nodule count affects graphite size and shape. Increasing nodule count results in a decrease in nodule size which improves tensile, fatigue and fracture properties. Inoculation practices used to improve nodule count often make the nodules more spherical. Thus, high nodule count is generally associated with improved nodularity.

Effect of Graphite Volume

The volume fraction of graphite in Ductile Iron can also influence certain tensile properties. Figure 3.14 illustrates the effects of carbon content (at constant silicon level) and casting diameter on the Dynamic Elastic Modulus of a Ductile Iron casting with a fully pearlitic matrix. Increasing the carbon content, which increases the volume fraction of graphite, decreases the DEM for a constant section size. Casting section size can influence both the volume fraction and size of graphite nodules. Increased section size reduces the cooling rate of the casting, causing more carbon to precipitate in the stable graphite phase, instead of the carbide phase favoured by higher cooling rates. The lower cooling rates of the larger diameter bars also affect graphite nucleating conditions, resulting in reduced nodule count but increased nodule size. The increase in nodule size with section size is the primary cause of the reduced DEM, but an increase in the formation of graphitic carbon during solidification could also be a contributing factor.

Figure 3.15



Relationships between tensile properties and pearlite contents of as-cast Ductile Iron.

SECTION III

Graphite flotation can produce variations in graphite volume within larger castings which can be harmful to mechanical properties. Graphite flotation occurs when low cooling rates and high "carbon equivalent" (carbon equivalent = % carbon + 1/3 (% silicon)) combine to produce large nodules that rise during solidification. The result is a depletion of the larger nodules in the lower part of the casting and an accumulation at the upper surface. The increasingly pronounced curvature, with increasing bar diameter, of the curves in Figure 3.14 is probably an indication of graphite flotation. In these larger bars, graphite flotation at higher carbon levels may have reduced the graphite volume in the center of the bars from which the 1/4 inch (6 mm) diameter test bars were machined. The resultant reduced rate of increase of graphite volume with increased carbon would be reflected in flatter curves at higher carbon levels.

Graphite flotation can cause a serious degradation of properties near the upper (cope) surface of large Ductile Iron castings. However, this phenomenon is readily avoided by reducing the carbon equivalent as the casting section size increases.

SECTION III

Effect of Carbide Content

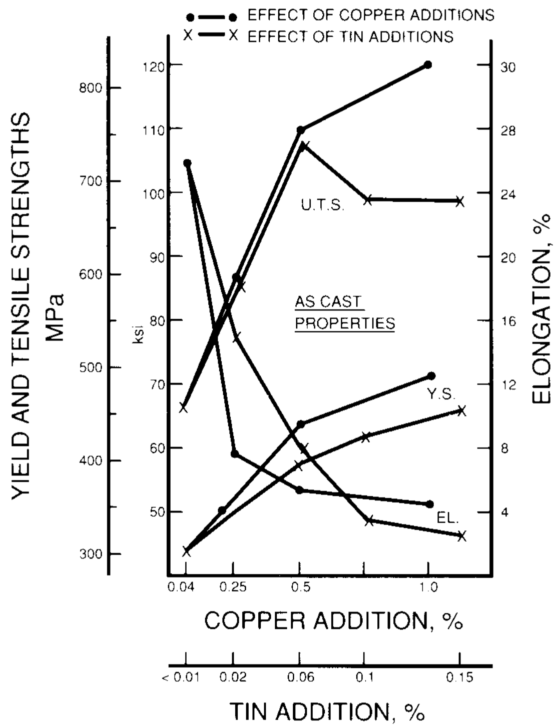
Carbide content has both direct and indirect effects on the properties of Ductile Iron castings. Figures 3.12 and 3.13 show that increasing the volume per cent of hard, brittle carbide increases the yield strength, but reduces the tensile strength of Ductile Iron castings. As discussed earlier, this convergence of yield and tensile strengths produces a decrease in elongation with increasing carbide content. The presence of carbides in a Ductile Iron matrix also increases the dynamic elastic modulus and significantly reduces machineability. The formation of eutectic carbide during solidification affects the volume fraction of graphite produced because carbide and graphite compete for the carbon contained in the liquid iron. Fifteen volume per cent of carbide would require 1 per cent carbon, reducing the carbon available for graphite by approximately one-third. The formation of carbide thus increases the likelihood of internal casting porosity by reducing the expansion effects produced by the formation of graphite during solidification.

To minimize the detrimental effects on properties and machinability, maximum carbide levels of less than 5% are normally specified. These levels can usually be achieved as-cast by reducing the levels of carbide forming elements through the use of high purity pig iron in the furnace charge and by increasing the nodule count through the application of good inoculation practices. When required, heat treatment can be used to eliminate carbides.

Effect of Matrix

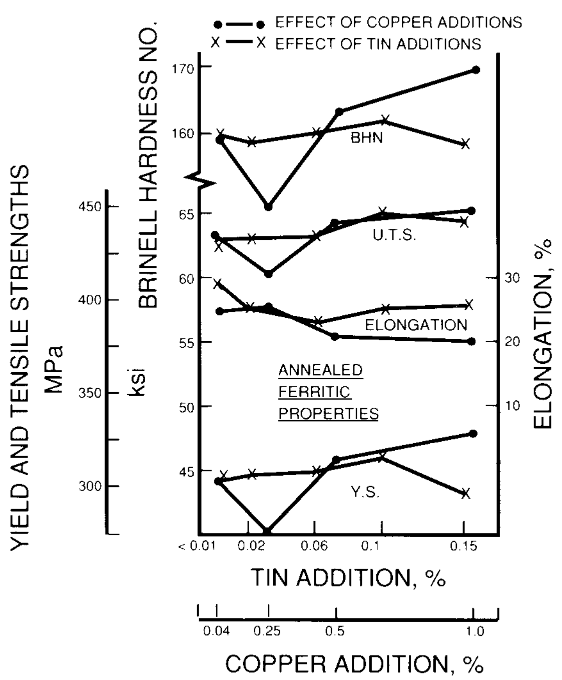
In Ductile Irons with consistent nodularity and nodule count and low porosity and carbide content, mechanical properties are determined primarily by the matrix constituents and their hardness. For the most common grades of Ductile Iron, the matrix consists of ferrite and/or

Figure 3.16



Tensile properties of as-cast Ductile Irons with different Cu and Sn contents.

Figure 3.17



Tensile properties of annealed (ferritic) Ductile Irons with different Cu and Sn contents.

pearlite. Ferrite is the purest iron phase in Ductile Iron. It has low strength and hardness, but high ductility and toughness and good machinability. Pearlite is an intimate mixture of lamellar cementite in a matrix of ferrite. Compared to ferrite, pearlite provides a combination of higher strength and hardness and lower ductility. The mechanical properties of ferritic/pearlitic Ductile Irons are, therefore, determined by the ratio of ferrite to pearlite in the matrix. This ratio is controlled in the as-cast condition by controlling the composition of the iron, taking into account the cooling rate of the casting. It can also be controlled by an annealing heat treatment to produce a fully ferritic casting, or by normalizing to maximize the pearlite content. Annealing, normalizing and other Ductile Iron heat treatments are discussed in Section VII.

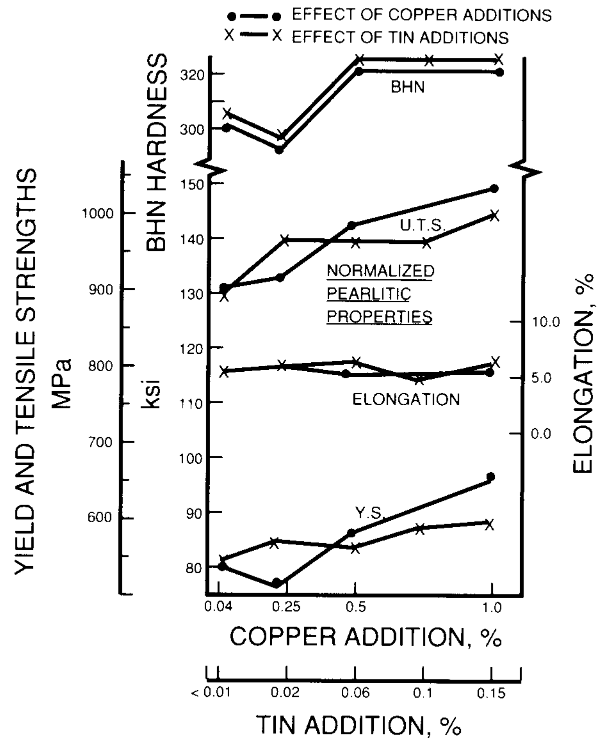
Figure 3.15 shows the correlation between tensile properties, hardness and pearlite content in as-cast 1 inch (25 mm) keel blocks. The pearlite content was varied from 15 to 100 per cent by the use of different copper-manganese and tin-manganese combinations. Alloy levels beyond those required to produce a fully pearlitic matrix were also tested to determine their effects on properties. The apparent variation in properties at the 100% pearlite level is therefore not due to scatter in the data but an indication of the effects of higher alloy contents. Figure 3.15 reveals the remarkable consistency in the relationships between mechanical properties and pearlite content for all pearlite levels below 100 per cent, regardless of whether they were produced by Cu or Sn additions.

The effects of Cu and Sn diverge, however, for alloy levels approaching and exceeding those required to produce a fully pearlitic matrix. Additions of copper to a fully pearlitic matrix in the Cu-Mn alloy resulted in further increases in both yield and tensile strengths, probably due to solid solution strengthening. Additions of tin to the fully pearlitic Sn-Mn alloy did not affect the yield strength, but resulted in a decrease in tensile strength that has been related to the formation of intercellular degenerate graphite.

Figures 3.16-18 provide further evidence of the relationships between tensile properties and pearlite and ferrite contents in Ductile Iron castings in the as-cast, fully annealed and normalized conditions respectively. These data, obtained from testing 1 inch (25 mm) keel blocks made from irons with average compositions of 3.75% C, 2.50% Si and 0.23% Mn, also show the influence of varying levels of Cu and Sn on tensile properties. As-cast properties (Figure 3.16) vary mainly through the influence of Cu and Sn levels on the pearlite content of the matrix. Yield and tensile strengths increase, and elongation decreases, until the matrix becomes fully pearlitic at 0.5% Cu for the Cu-hardened alloy and at 0.06% Sn for the Sn-pearlitized alloy. In agreement with Figure 3.15, additions of Cu and Sn beyond these levels have opposite effects on the tensile properties of the two alloys, with the Sn alloy becoming weaker and less ductile.

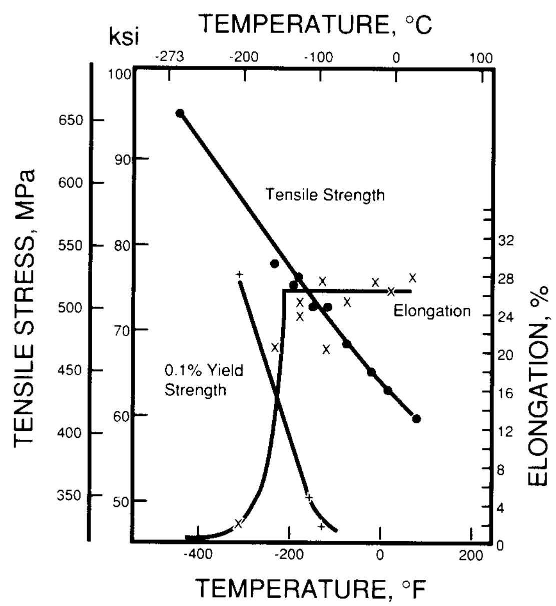
SECTION III

Figure 3.18



Tensile properties of normalized (pearlitic) Ductile Irons with different Cu and Sn contents.

Figure 3.19



Effect of temperature on the low-temperature properties of ferritic Ductile Iron.

Figure 3.17 shows that the tensile properties of an annealed, fully ferritic casting are relatively constant, and independent of the quantities of either Cu or Sn. The UTS and BHN data for the Cu alloyed material suggest a slight solution hardening that is not produced by Sn. Ferritization of the fully pearlitic samples containing more than 0.06% Sn has eliminated the embrittling effect seen in the as-cast condition. (These Sn levels are of academic interest only, as the Sn content in commercial Ductile Iron is usually limited to less than 0.05%.)

Both hardness and strength of the normalized keel blocks increase with increasing Cu and Sn contents (Figure 3.18). In the Cu alloyed material, the increase is due to solid solution strengthening, while the initial increase produced by Sn is caused by the elimination of ferrite rings around the graphite particles, indicating that for the Sn series, the base composition provided insufficient hardenability for complete pearlitization.

The exceptional as-cast properties of the fully ferritic, base material – 66 ksi UTS, 45 ksi YS and 26% elongation for a Quality Index of 113: – are noteworthy. The Quality Indices of the heat treated samples, which were taken from different keel blocks, ranged from 90 to 113.

SECTION III

Low Temperature Tensile Properties

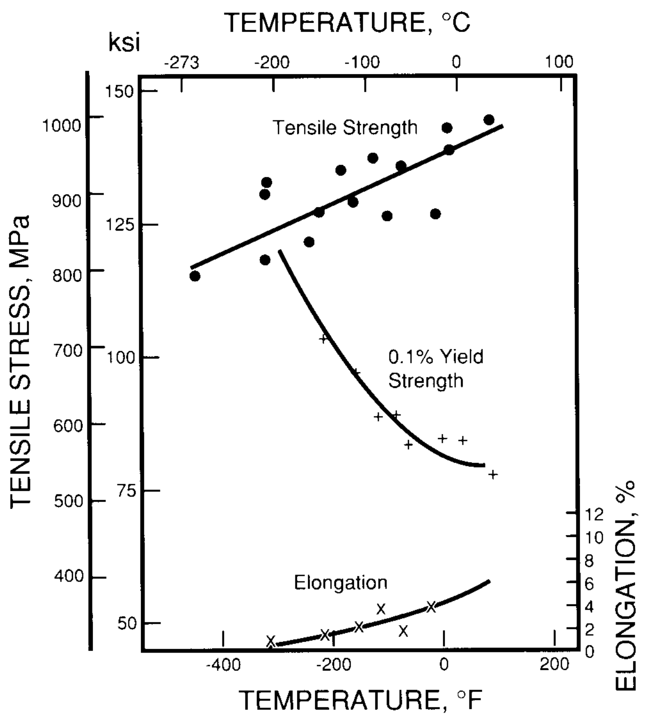
Ductile Irons are structurally stable at very low temperatures, but when designing for low temperature applications, the designer must take into consideration the significant effect of temperature on strength and elongation. Ferritic grades of Ductile Iron are generally preferred for low temperature applications because their ductility at low temperatures is superior to that of pearlitic grades. Figure 3.19 illustrates the effect of decreasing temperature on the tensile properties of an annealed ferritic Ductile Iron. As the temperature decreases, both the yield and tensile strengths increase, although the yield strength, which more accurately reflects the effect of temperature on flow stress, rises more rapidly. The room temperature elongation of 25% is maintained to very low temperatures, – 200 °F (– 130 °C), but as the yield and tensile stresses converge, the elongation decreases rapidly to less than 2% at – 330 °F (– 200 °C).

Pearlitic grades of Ductile Iron exhibit a significantly different response to decreasing temperature. Figure 3.20 shows that as the test temperature decreases, the yield strength increases, but the tensile strength and elongation decrease continuously. As a result of the steady deterioration in tensile strength and elongation below room temperature, pearlitic Ductile Irons should be used with caution at low temperatures.

High Temperature Tensile Properties

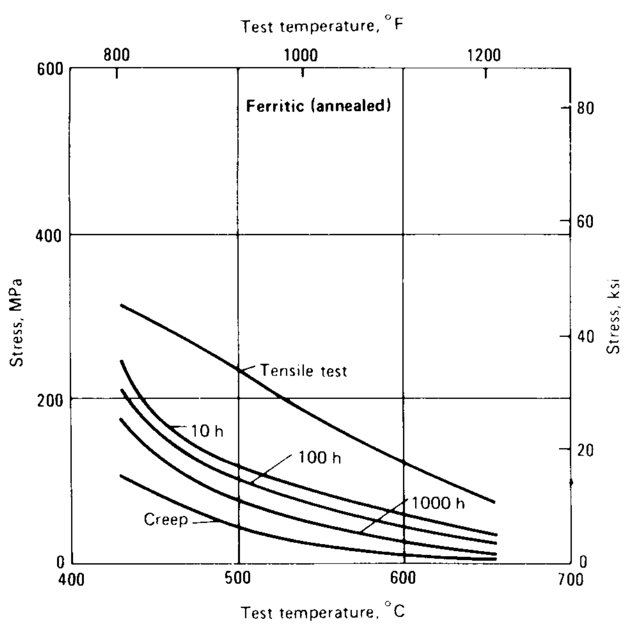
Ductile Irons exhibit several properties which enable them to perform successfully in numerous elevated temperature applications. Unalloyed grades retain their strength to moderate temperatures and exhibit significantly better resistance to growth and oxidation than unalloyed Gray

Figure 3.20



Effect of temperature on the low-temperature properties of pearlitic Ductile Iron.

Figure 3.21



Tensile, creep rupture and creep behaviour of ferritic Ductile Iron.

Iron. Alloy Ductile Irons (see Section V) provide outstanding resistance to deformation, growth and oxidation at high temperatures. The only high temperature applications in which Ductile Irons, with the exception of Type D-5 Ductile Ni-Resist, do not perform well are those involving severe thermal cycling. In these applications the low thermal conductivity of Ductile Iron, combined with a high modulus of elasticity, can result in internal stresses high enough to produce cracking and warpage. However, the successful use of Ductile Iron in millions of exhaust manifolds and turbocharger casings confirms that in specific thermal cycling applications Ductile Iron provides superior performance.

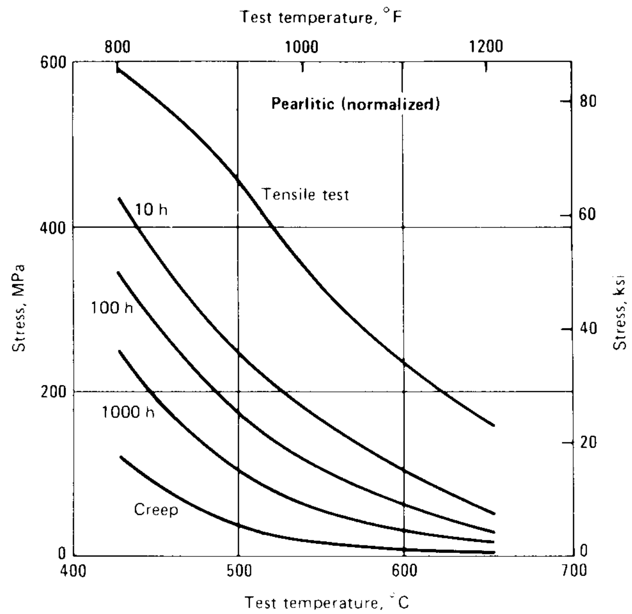
Figures 3.21 and 3.22 show that the short-term, elevated temperature tensile strengths of unalloyed ferritic and pearlitic Ductile Irons initially decrease slowly, losing only about one-third of their values between room temperature and 425 °C (800 °F). Above this temperature the tensile strengths of both grades decrease rapidly with further increases in temperature. The pearlitic grade exhibits superior strength at all temperatures, due to a combination of higher ambient temperature strength and reduced effect of temperature on strength. Figures 3.21 and 3.22 also describe both stress-rupture and creep behaviour above 425 °C (800 °F). The stress-rupture curves define the stress required to produce rupture failures after 10, 100 and 1000 hours. The creep curves define the stress required at a given temperature to produce a minimum creep rate of 0.0001%/h for both grades. As with the tensile properties, the short-term stress-rupture strength of the pearlitic grade is approximately twice that of the ferritic grade. However, the longer term rupture strength and creep strength of both materials are almost identical. The relatively poor longer term rupture and creep properties of the pearlitic iron, compared to its shorter term properties, are partly due to growth from graphitization and ferritization of the pearlite matrix.

Figure 3.23 is a Larson Miller Diagram which relates the high temperature creep and stress-rupture properties of unalloyed ferritic Ductile Iron to a combination of time and temperature. For example, a sample subjected to a stress of 4 ksi would be expected to have lives of 10, 100 and 1000 hours when tested at temperatures of 675, 625 and 595 °C (1245, 1160, and 1100 °F). Figure 3.23 also shows that the creep and stress-rupture properties of Ductile Iron can be improved substantially by increasing the silicon content and adding molybdenum and aluminium. The effect of alloying elements on the high temperature properties of Ductile Iron will be presented in greater detail in Section V.

Effect of Temperature on Design Stresses

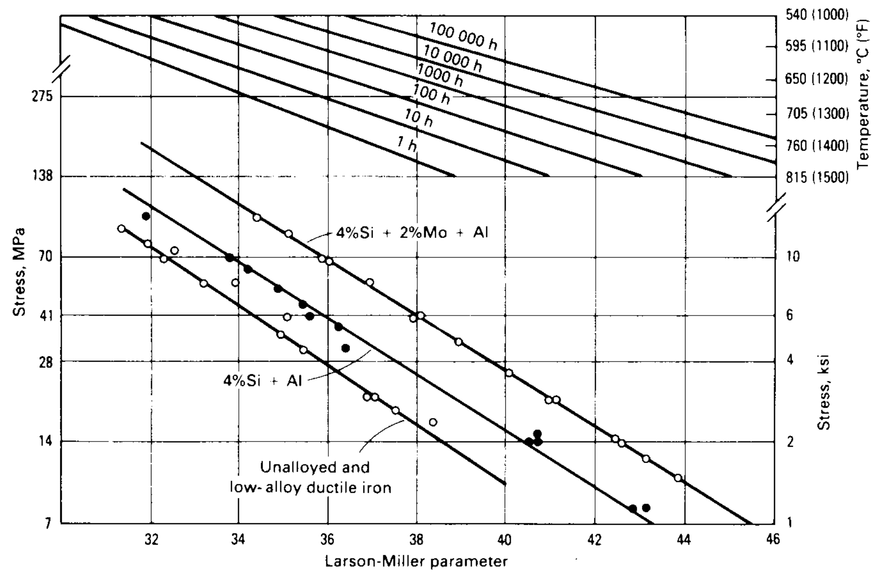
When determining design stresses for a Ductile Iron component, the designer must be aware of both the temperature range in which the component will be operated and the effect of temperature on tensile properties. The increase in yield strength with decreasing temperature for both ferritic and pearlitic Ductile Irons suggests that higher design stresses

Figure 3.22



Tensile, creep rupture and creep behaviour of pearlitic Ductile Iron.

Figure 3.23



Larson-Miller diagram defining the stress-rupture behaviour of unalloyed, low-alloy and Si-Mo-Al Ductile Irons.

SECTION III

may be used at low temperatures. Because most low temperature applications also involve performance at room temperatures, the room temperature yield strength must be used in the calculation of design stresses. However, the use of a yield strength-related design stress is acceptable for low temperature applications only when the applied stress state can be simulated by a quasi-static (low strain rate) test. In such cases, both ferritic and pearlitic grades may meet the design criteria. If the application involves impact loading, or if good notch toughness is specified, selection should be limited to ferritic grades. For special low temperature applications requiring maximum elongation and toughness, annealed ferritic grades should be used.

For temperatures up to 575 °F (300 °C), static design stresses can be based on the room temperature yield strength, as described earlier in this section. For temperatures above 650 °F (350 °C), design stresses should be related to creep data for applications in which dimensional accuracy is critical or stress rupture data when deformation can be tolerated but time-to-failure is critical.

Growth and Oxidation

The microstructural stability of unalloyed Ductile Irons at elevated temperatures depends primarily upon the matrix structure and the temperature. Ferritic Ductile Irons are stable up to a critical temperature of about 1350 °F (730 °C), while pearlitic grades exhibit growth through graphitization of the carbide component of the pearlite at temperatures above 1000 °F (540 °C). Above 1500 °F (815 °C) both ferritic and pearlitic grades of unalloyed Ductile Iron exhibit significant growth, with pearlitic grades growing more rapidly due to graphitization. Growth decreases with increasing section size and can be retarded by increasing the silicon content and alloying with chromium and molybdenum. Gray Iron, which grows by both graphitization and oxidation, exhibits higher growth rates than Ductile Iron. Table 3.1 compares the oxidation of different Ductile Irons and Gray Iron. Unalloyed Ductile Iron exhibits one-half the weight gain shown by Gray Iron. Increases in silicon content and additions of aluminium and molybdenum significantly decrease the oxidation of ferritic Ductile Iron to levels shown by the higher alloy, austenitic grades.

Effect of Environment on Tensile Properties

Like some steels, the ambient temperature tensile properties of certain grades of Ductile Iron can be reduced significantly by prolonged exposure to certain environments. Figure 3.24 summarizes the effects of exposure for 30 days to air-saturated, distilled water on the tensile properties of Ductile Iron samples with different hardness levels. Yield strength was not affected by exposure until hardness exceeded 275 BHN, above which it decreased rapidly, attaining a loss of over 40% at a hardness of 430 BHN. Tensile strength and elongation followed similar trends, but the loss of strength and ductility began at lower hardness levels, 175 BHN, and increased more slowly, attaining the same level of reduction (40%) at 430 BHN. Figure 3.24 indicates that exposure to

Table 3.1

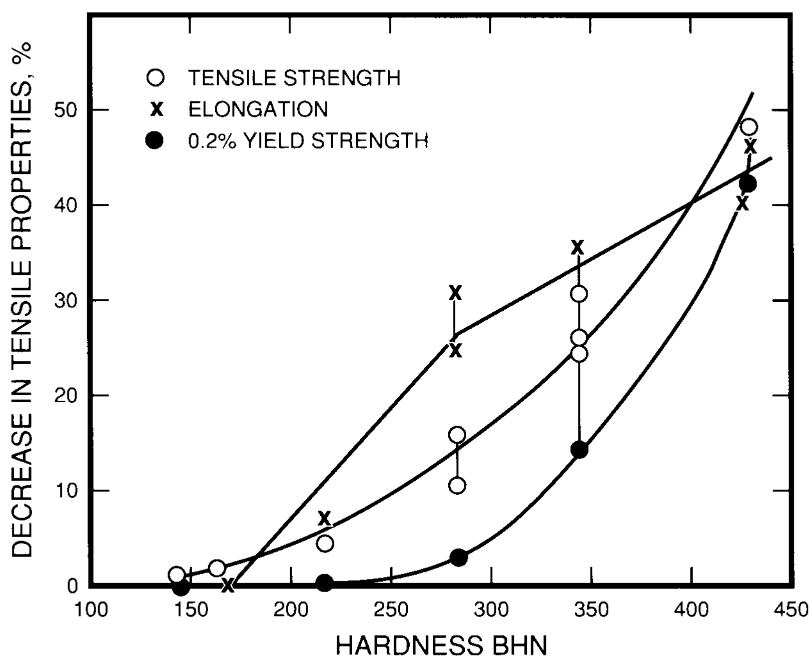
Type of Iron	Analysis, Percent Silicon	Alloys	Weight Gain* mg/cm²	Oxide Depth mils	*mm*
Ferritic Ductile	2.8		119.9	18.6	*0.47*
Ferritic Ductile	4.0	0.8 Al	6.3	3.5	*0.09*
Ferritic Ductile	4.2	1.9 Mo 0.6 Al	22.8	5.8	*0.15*
Ferritic Ductile	3.8	2.0 Mo 1.0 Al	15.2	3.7	*0.09*
Ferritic Ductile	4.0	2.0 Mo 0.9 Al	6.2	2.7	*0.07*
Austenitic Ductile	2.5	22.5 Ni 0.4 Cr	81.6	24.1	*0.61*
Austenitic Ductile	5.5	30.0 Ni 5.0 Cr	7.2	1.5	*0.04*
Austenitic Ductile	2.2	35.0 Ni 2.5 Cr 1.0 Mo	30.0	9.3	*0.24*
Gray Iron	2.0	0.14 Cr	217.2	35.3	*0.09*

* Net gain, oxidation minus decarburization.

Oxidation behaviour of ferritic and austenitic Ductile Irons in flowing air at 1500°F (815°C) for 500 hours.

SECTION III

Figure 3.24



Degradation of tensile properties of Ductile Irons with different hardness levels after exposure to water for 30 days.

water for 30 days has no significant effect on the tensile properties of ferritic Ductile Irons, but those quenched and tempered to produce hardness levels above 250 BHN are embrittled to a degree which increases with hardness. Embrittlement may be due to a hydrogen-related phenomenon similar to that occurring in high strength steels.

Fatigue Strength

A fatigue failure occurs in a metal component by the initiation and propagation of a crack under cyclic loading conditions. Fatigue failures play a significant role in machine design and materials selection for the following reasons.

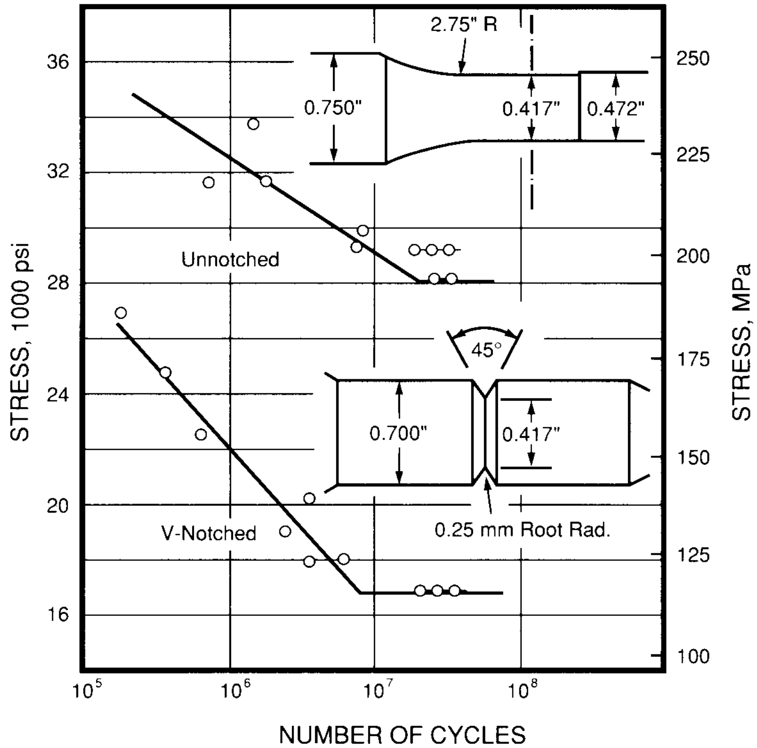
- Fatigue is probably the primary cause of 75% of the service failures occurring in machines.
- Fatigue failures can occur at stress amplitudes considerably below the yield strength.
- Stress concentrations such as material flaws or abrupt changes in component cross-section are much more harmful to material performance under fatigue conditions than under monotonic tensile loading.
- Fatigue cracks can grow slowly and without an easily detectable change in component dimension or performance. Upon reaching a critical size, catastrophic failure occurs.
- Design stresses based on fatigue criteria will be lower than those determined using monotonic tensile design values and will be reduced further by stress concentrations caused by material flaws or component design.

The fatigue behaviour of a material is defined by its Fatigue Life – the number of stress or strain cycles at which failure occurs. The fatigue data for a material are normally plotted on a semi-logarithmic graph of stress amplitude versus the log of the number of cycles to failure. The resultant S-N curve defines the relationship between the stress amplitude (S) and the number of cycles to failure (N) when the mean stress is zero. Fatigue data are also plotted on Goodman Diagrams to define fatigue behaviour for non-zero mean stresses.

Fatigue Limit

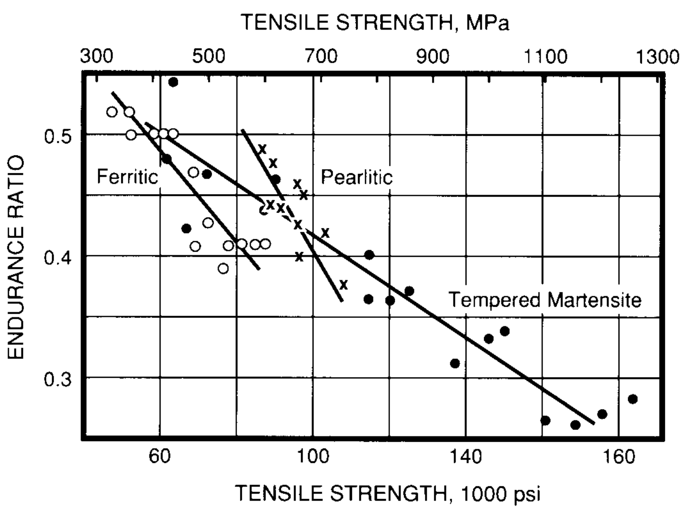
The fatigue strength of a material is normally defined by quoting its fatigue limit, also called the endurance limit. The fatigue limit is the magnitude of the cyclic stress at which the fatigue life exceeds a specified number of cycles, usually 10^6 or 10^7. The fatigue strength of a material is related to its tensile strength by the endurance ratio – the ratio of fatigue limit to tensile strength. The effect of stress-raisers on the fatigue limit is defined by the notch sensitivity ratio, also known as the fatigue strength reduction factor. The notch sensitivity ratio is the ratio of unnotched fatigue limit to notched fatigue limit. The fatigue limit of a Duc-

Figure 3.25



Typical S-N curves for notched and unnotched ferritic Ductile Irons.

Figure 3.26



Relationships between endurance ratio, tensile strength and matrix microstructure for Ductile Iron.

tile Iron component is influenced by the following factors: tensile strength, the size, shape and distribution of graphite nodules, the volume fractions of inclusions, carbides and dross, the quantity and location of porosity, the presence of stress-raisers, and the condition of the component surface.

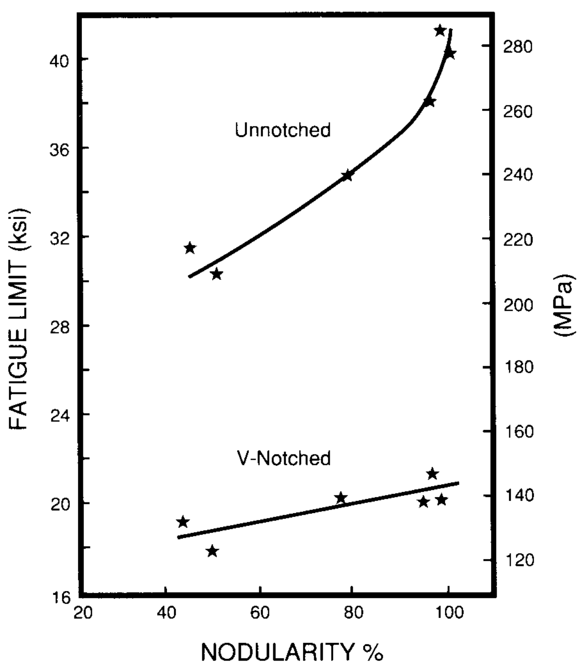
Figure 3.25 illustrates S-N curves for notched and unnotched annealed ferritic Ductile Iron with a tensile strength of 65.8 ksi (454 MPa). With notched and unnotched fatigue limits of 17 ksi (117 MPa) and 28 ksi (193 MPa) respectively, this material has notch sensitivity factor of 1.65 and an endurance ratio of .43. The endurance ratio of Ductile Iron depends upon the tensile strength and matrix. Figure 3.26 shows that the endurance ratios of ferritic and pearlitic grades are similar, decreasing from 0.5 to 0.4 with increasing strength within each grade. For tempered martensite matrices, the endurance ratio decreases from 0.5 at a tensile strength of 60 ksi (415 MPa) to 0.3 at a UTS of 150 ksi (1035 MPa).

SECTION III

Effect of Nodule Shape and Size

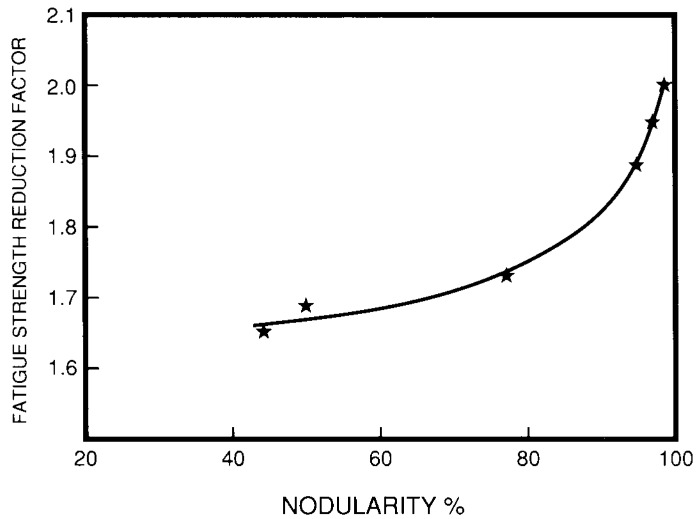
Figure 3.27 shows the influence of nodularity on the notched and unnotched fatigue limits of pearlitic Ductile Iron. The notched fatigue limit varies very little over a wide range of nodularity, while the unnotched fatigue limit increases rapidly with nodularity, especially at very high nodularities. These results indicate that non-spherical graphite initiates fatigue failure in unnotched Ductile Iron, while in v-notched specimens, the crack initiates prematurely in the notch, over-riding any effect of nodularity.

Figure 3.27



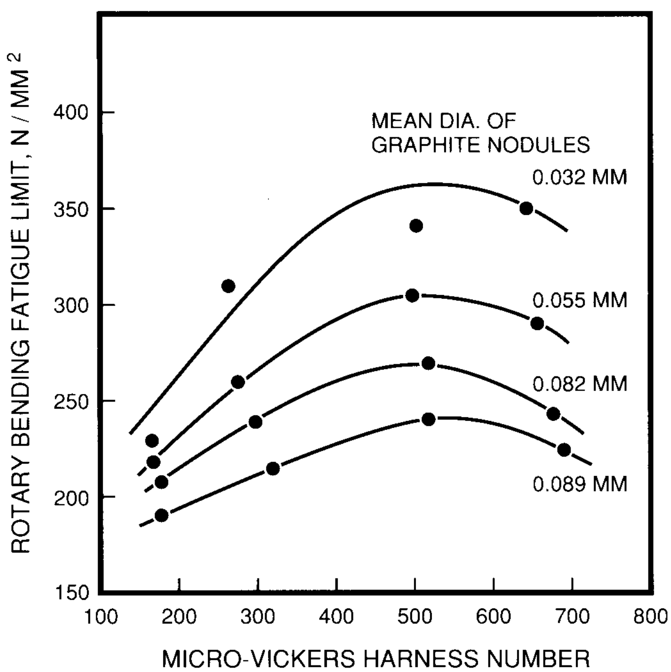
Effect of nodularity on notched and unnotched fatigue limits of pearlitic Ductile Iron.

Figure 3.28



Effect of nodularity on fatigue strength reduction factor of pearlitic Ductile Iron.

Figure 3.29



Effect of nodule size and matrix micro-hardness on fatigue limit of Ductile Iron.

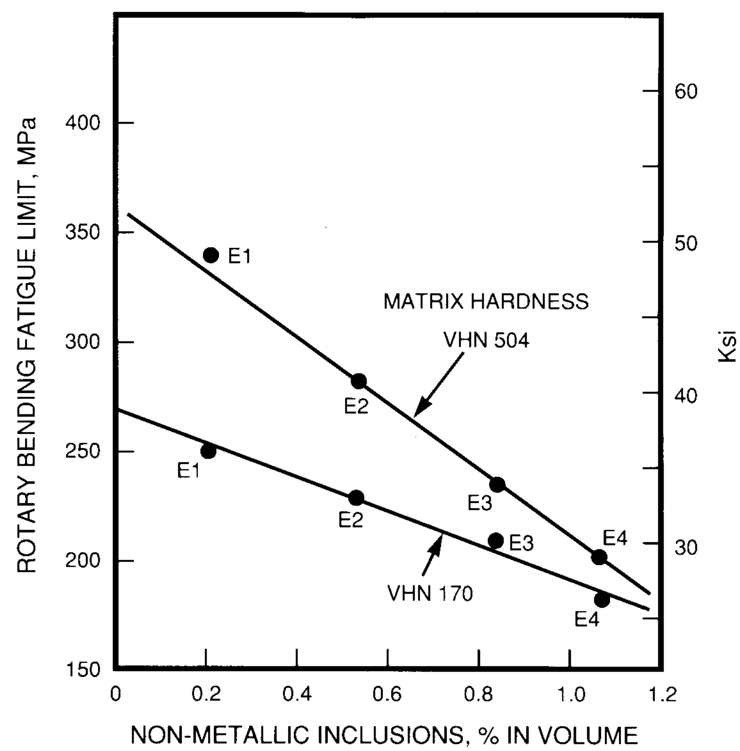
The net result of the different effects of nodularity on notched and unnotched specimens is the variation of fatigue strength reduction factor (notch sensitivity ratio) with nodularity shown in Figure 3.28, in which notch sensitivity increases with increasing nodularity. Figure 3.29 illustrates the effect of nodule size on the fatigue limits of Ductile Irons with different matrix hardness. At all levels of hardness, fatigue strength increases as nodule size decreases, but the effect of nodule size is most pronounced as hardness increases.

Effect of Metal Cleanliness

Under bending and torsional fatigue conditions in which the cyclic stresses reach a maximum at the component surface, fatigue strength is reduced by the presence of inclusions, dross, and other surface defects which act as crack initiation sites. Figure 3.30 shows that increasing the volume fraction of non-metallic inclusions significantly decreases fatigue strength. The influence of non-metallic inclusions on fatigue strength increases as matrix hardness increases. The increasing use of Ductile Iron components with as-cast surfaces places an increased importance on the elimination of surface defects for applications requiring optimum fatigue strength.

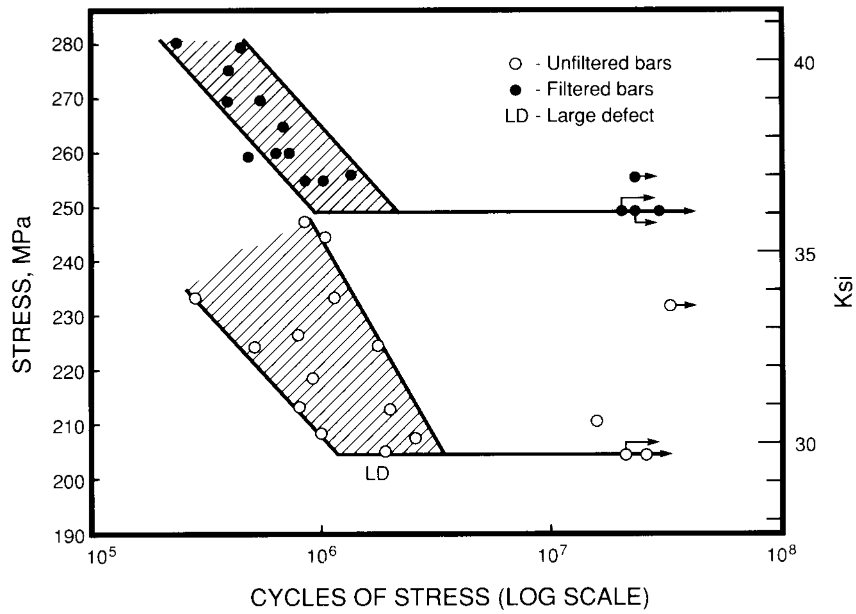
SECTION III

Figure 3.30



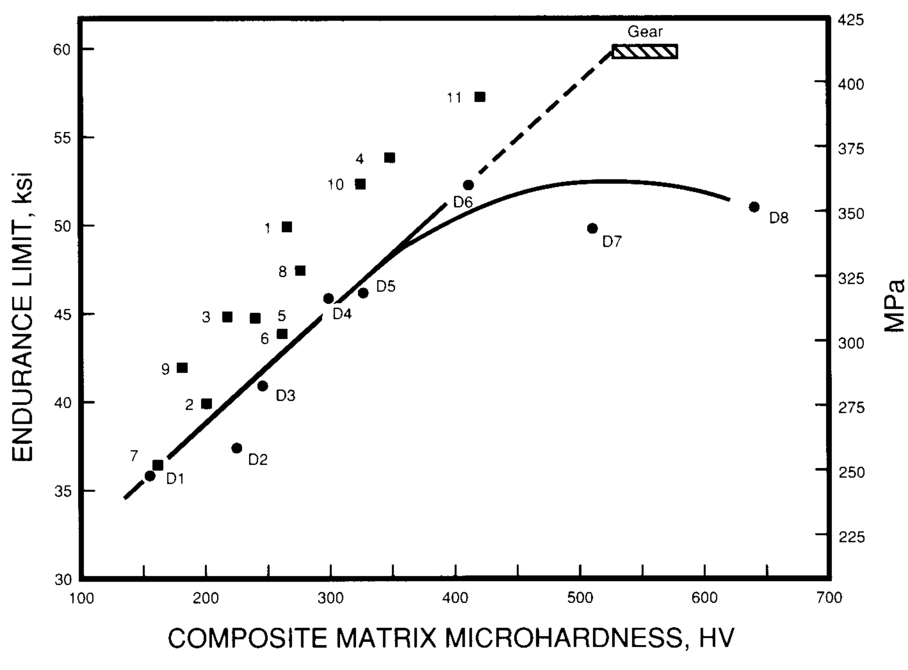
Effect of matrix micro-hardness and volume fraction of inclusions on fatigue limit of Ductile Iron.

Figure 3.31



Effect of filtration on the fatigue limit of ferritic Ductile Iron with an as-cast surface.

Figure 3.32



Relationship between fatigue strength and composite matrix microhardness (CMMH). "Gear" indicates performance of pearlitic Ductile Iron gears with hardened teeth.

The reduction of dross-related surface defects through the use of filters in the mold filling system can result in a 25 per cent increase in fatigue life, as shown in Figure 3.31. The use of good foundry practices, including minimizing residual Mg content, careful deslagging of ladles, good gating and pouring practices, the use of filters in the gating system and the reduction of the effects of flake-forming elements in both the metal and molding materials, can result in fatigue strengths for as-cast surfaces that are within 5 per cent of those obtained on components with machined surfaces.

Effect of Matrix

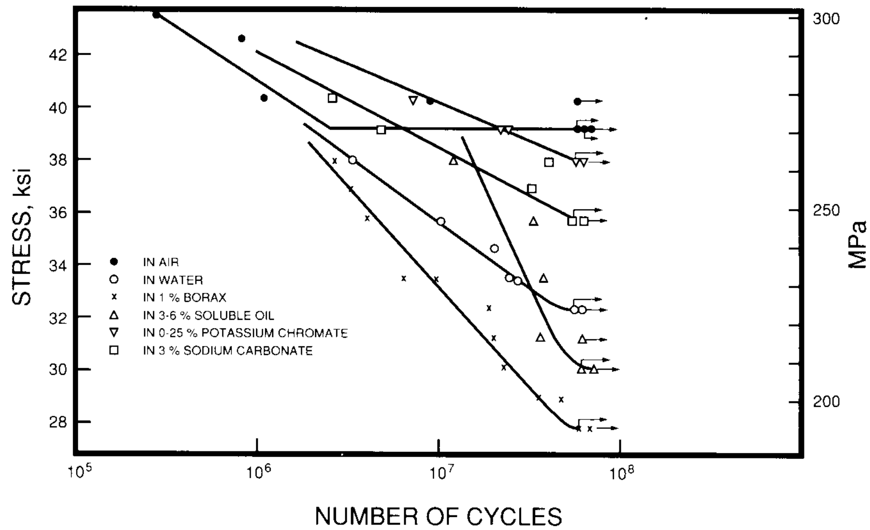
Figures 3.26, 3.29 and 3.30 indicate that matrix type and related mechanical properties, especially tensile strength and hardness, exert considerable influence on fatigue strength. However, the decrease in endurance ratio with increasing tensile strength in Figure 3.26 indicates that increasing the tensile strength of Ductile Iron does not provide a proportionate increase in fatigue strength. Figure 3.29 shows that, for constant nodule size, fatigue strength increases with Vickers micro-hardness number, reaching a maximum at a hardness value of 500. Examination of Figure 3.30 reveals a significant influence of matrix micro-hardness on fatigue strength at low inclusion levels, which declines as the volume fraction of inclusions increases.

Figure 3.32, from Janowak, Alagarsamy and Venugopalan, indicates that there is a good correlation between fatigue strength and the calculated composite matrix micro hardness (CMMH). (See Figure 3.9 for a similar relationship between tensile properties and CMMH.) Figure 3.32 also includes the data of Sofue et al, from whose work Figures 3.29 and 3.30 are taken. The region marked ''gear'' in this Figure refers to data reported by Sofue et al on the successful performance of pearlitic Ductile Iron gears with induction hardened teeth. It is interesting to note that the fatigue performance of commercial Ductile Irons shown in Figure 3.32 is superior, at equal hardness, to that of the irons produced in the laboratory by Sofue et al (D1-D8). Janowak et al attributed the inferior performance of the laboratory irons to low alloy and residual element contents, and the quench and temper heat treatments used by Sofue et al to produce different matrix hardness levels. Nevertheless, Figure 3.32 confirms that a good correlation exists between matrix microhardness and fatigue strength and that the fatigue performance of Ductile Iron can be predicted using the calculated CMMH.

Effect of Environment

Because fatigue failures generally occur after a significant period of time has elapsed, fatigue behaviour can be degraded significantly by environments which accelerate crack initiation and growth. Figure 3.33 illustrates the reduction in fatigue strength resulting from exposure to water spray environments consisting or water and aqueous solutions of borax, sodium carbonate, and a soluble oil. In the most aggressive environment, borax, fatigue strength was reduced by 28 per cent. In accord with the time-dependent nature of corrosion-assisted fatigue, the effect of the

Figure 3.33



Effect of different water spray environments on fatigue strength of pearlitic Ductile Iron.

Table 3.2

Surface Treatment	**As-machined**		**Zinc-sprayed**		**Aluminium-sprayed**	
Environment	Fatigue Strength MPa (ksi)	Fatigue Strength Reduction Factor	Fatigue Strength MPa (ksi)	Fatigue Strength Reduction Factor	Fatigue Strength MPa (ksi)	Fatigue Strength Reduction Factor
Air	270 (39.2)	N/A	286 (41.5)	0.96	293 (42.5)	0.92
Water	224 (32.5)	1.21	270 (39.2)	1	278 (40.3)	0.97
3% NaCl	46 (6.7)	5.83	278 (40.3)	0.97	270 (39.2)	1

Effect of environment and coatings on corrosion fatigue strength of pearlitic Ductile Iron.

SECTION III

corrosive environments decreased with decreasing fatigue life. Only potassium chromate, an inhibitor, prevented any significant loss in fatigue strength due to exposure to an aqueous environment. Chromate solutions are now considered to be toxic, and a combination of 0.5% sodium nitrate and 1% sodium silicate has been shown to be equally effective. Table 3.2 shows that spray coatings of zinc and aluminium provide excellent protection against corrosion fatigue of Ductile Iron by water and brine spray environments. Uncoated samples showed fatigue strength reductions of 1.2 and 5.8 times respectively in water and brine sprays, while zinc- and aluminium-coated samples showed no loss of fatigue strength.

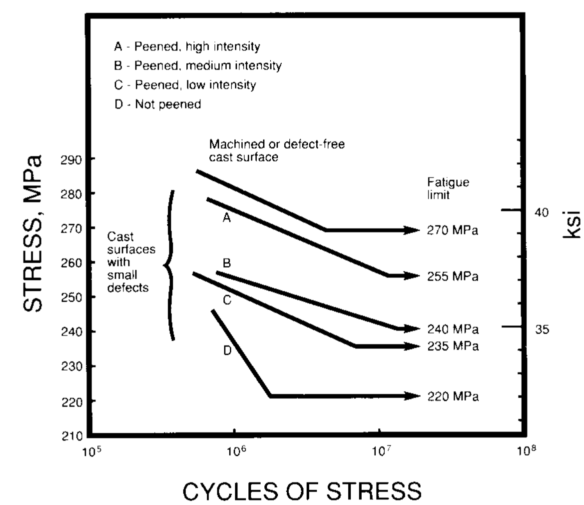
Effect of Surface Conditions

In bending and torsional fatigue, in which cyclic stresses attain maximum values at the component surface, fatigue behaviour is strongly dependent upon surface geometry, residual stress conditions and material properties in the surface layer of the component. The use of adequate fillet radii, shot peening, surface rolling, flame and induction hardening and nitriding can significantly increase the fatigue limit ot Ductile Iron components. These treatments, which will be discussed in more detail in Section IX, enhance fatigue resistance by 20 to 100 per cent by increasing the tensile strength and inducing compressive stresses in the surface layer of the component. In addition to improving surface stress conditions, shot peening also reduces the stress concentration effects of surface roughness.

Shot Peening & Surface Rolling

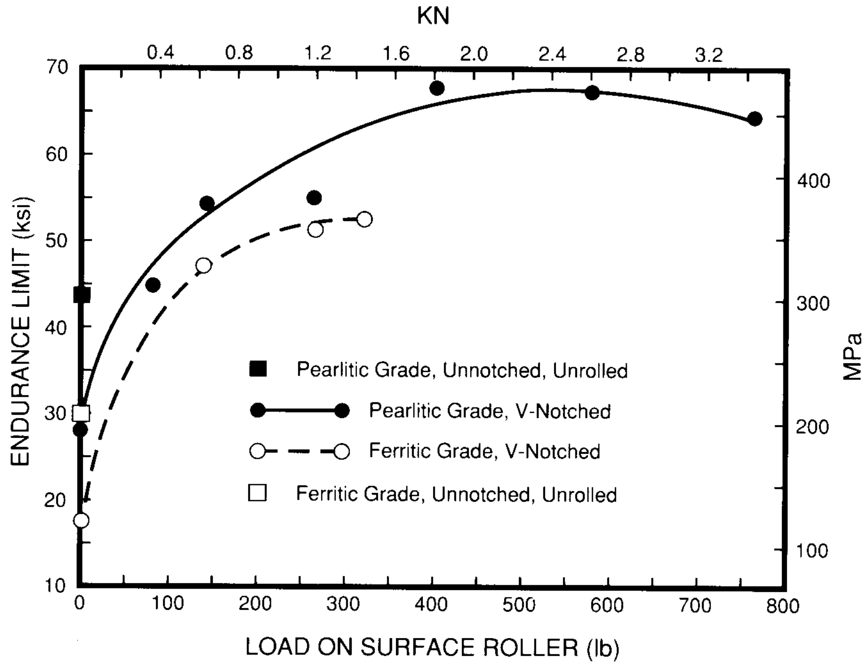
Figure 3.34 illustrates the effect of different levels of shot peening intensity on the fatigue strength of pearlitic Ductile Iron with as-cast surfaces. Shot peening at the highest intensity level developed fatigue properties of the as-cast surfaces to within 6 per cent of those with defect-free machined surfaces.

Figure 3.34



Effect of different shot peening intensities on the fatigue strength of pearlitic Ductile Iron with as-cast surfaces.

Figure 3.35



Influence of surface rolling on the v-notched fatigue strength of ferritic and pearlitic Ductile Iron.

Table 3.3

Material / Processing	Endurance limits, ksi	MPa
Crank type 202		
Ductile IRON, as-cast	30*	207
Ductile IRON, as-cast, rolled fillets	97	669
Ductile IRON, austempered	60	414
Ductile IRON, austempered, rolled fillets	143	986
Steel - 1046 Q&T	48*	331
Crank type 303		
Ductile IRON, as-cast, rolled fillets	83	572

* Previously determined.

Effect of fillet rolling and austempering on reversed bending fatigue properties of crankshafts.

Figure 3.35 illustrates the influence of surface rolling on the bending fatigue properties of ferritic and pearlitic grades of Ductile Iron. This Figure shows that v-notched samples, strengthened by rolling with a roller contoured to the notch geometry, had fatigue strengths from 58 to 73 per cent higher than the unnotched samples of the pearlitic and ferritic grades respectively. Table 3.3, which compares the reversed bending fatigue properties of different Ductile Iron crankshafts, confirms the significant strengthening effect of fillet rolling. Fillet rolling of as-cast crankshafts increased fatigue strength from 30 ksi (207 MPa) to 83-97 ksi (572-669 MPa), an increase of 175-225 per cent over the as-cast pearlitic iron. This Table also documents the even greater benefits accruing from austempering and fillet rolling (see Section IV for more information on the fatigue properties of austempered Ductile Iron).

Surface Heat Treatment

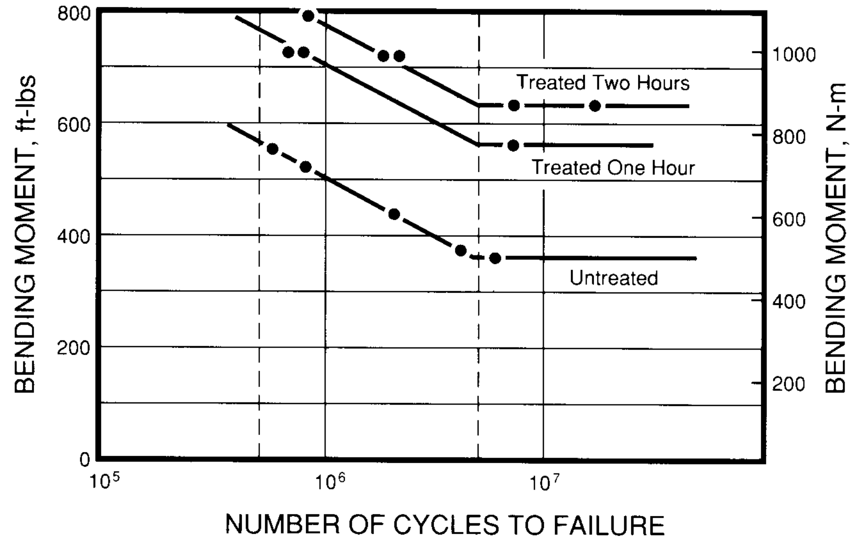
Surface hardening by flame or induction heating is used to improve the resistance of Ductile Iron to both normal and pitting fatigue failures. Conventional fatigue strength is improved by a combination of high surface hardness and compressive surface stresses, while pitting fatigue is reduced by the increased surface hardness. Molten salt cyaniding produces a two-layer "case" on Ductile Iron components which can result in increases in fatigue strengths from 63 to 80 per cent, as shown in Figure 3.36.

Designing for Fatigue Applications

The design stress for fatigue should not exceed one-third of the fatigue limit measured under conditions that suitably replicate the stress environment of the application. That is, notched data should be used when unavoidable stress concentrations are present in the component, and bending, torsional and push-pull fatigue data should be used according to the type of cyclic stress encountered by the component. The fatigue strength of Ductile Iron is frequency sensitive, and test frequencies should not exceed those encountered when the component is in service. The fatigue strength of Ductile Iron, like many other cast materials, is also influenced by both the cast section size and the specimen size. Both of these factors should be considered when extrapolating laboratory fatigue data to actual components, although the one-third safety factor may be sufficient to compensate for any degradation in fatigue strength due to size factors. The fatigue strength of Ductile Iron can be optimized through a combination of production and design practices which result in the following component characteristics.

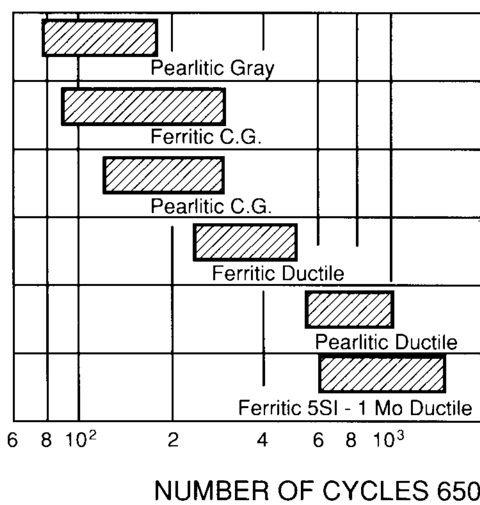
- maximum pearlite content and CMMH
- high nodularity and nodule count
- reduced nodule size
- high degree of cleanliness
- minimum shrinkage and porosity in critical areas

Figure 3.36



Influence of molten salt cyaniding treatment on fatigue strength of Ductile Iron.

Figure 3.37



	C	Si	Mn	P	Mg	
Pearlitic Gray	2.96	2.90	0.78	0.066	-	0.12 Cr
Ferritic C.G.	3.52	2.61	0.25	0.051	0.015	-
Pearlitic C.G.	3.52	2.25	0.40	0.054	0.015	1.47 Cu
Ferritic Ductile	3.67	2.55	0.13	0.060	0.030	-
Pearlitic Ductile	3.60	2.34	0.50	0.053	0.030	0.54 Cu
Ferritic 5SI - 1 Mo Ductile	3.48	4.84	0.31	0.067	0.030	1.02 Mo

Comparison of the thermal fatigue properties of Gray, Compacted Graphite and Ductile Irons.

- minimum carbide content
- freedom from degenerate graphite and dross on as-cast surfaces
- reduction of stress concentrations in component design
- fatigue-strengthening surface treatments

Thermal Fatigue

Thermal fatigue is a special type of fatigue in which thermal cycling produces stress/strain cycles in the component through differential expansion and contraction resulting from temperature gradients. The severity of thermal fatigue increases with increased temperature, increased range over which the temperature is cycled and increased rates of heating and cooling. Material properties which contribute to good thermal fatigue resistance are: high thermal conductivity, low modulus of elasticity and high strength and ductility. For severe thermal fatigue conditions, the high thermal conductivity and low modulus of high carbon Gray Iron make this material superior to both conventional and alloyed ferritic Ductile Irons and Compacted Graphite (CG) Iron.

For medium severity thermal fatigue, ferritic Ductile Iron and CG Iron provide superior cracking resistance but may fail by distortion. Pearlitic and alloy Ductile Irons provide the best performance for low severity thermal fatigue conditions. Figure 3.37 shows the increasing superiority of ferritic, pearlitic and alloy Ductile Irons in the Buderus Test in which thermal fatigue resistance is ranked by measuring the number of cycles between 650 °C (1200 °F) and room temperature required to produce bridge cracking between two holes in the test specimen. Performance of exhaust manifolds follows closely the ranking shown in this Figure. Ferritic Ductile Iron exhaust manifolds have been used widely due to a combination of good thermal fatigue strength and resistance to graphitization. Recent demands for increased service temperatures have resulted in the use of "Si-Mo" Ductile Irons containing 4-5% Si and up to 1% Mo. The increased strength and oxidation resistance of these alloys have resulted in excellent performance at service temperatures up to 750 °C (1380 °F).

Fracture Behaviour

Ductile Iron, like most ferrous materials, exhibits fracture behaviour which varies according to composition, microstructure, temperature, strain rate, and stress state. At low temperatures, brittle failure occurs by the formation of cleavage cracks, producing a facetted, shiny fracture surface. Very little deformation is associated with this type of fracture, resulting in low absorption of energy and low toughness. As the temperature increases, producing a decrease in flow stress, failure occurs by plastic deformation, primarily by the formation, growth and coalescence of voids. The resultant fracture surface will be dull gray, and the energy absorbed will be high, meaning very good fracture toughness. Fracture in ferrous materials traditionally has been characterized

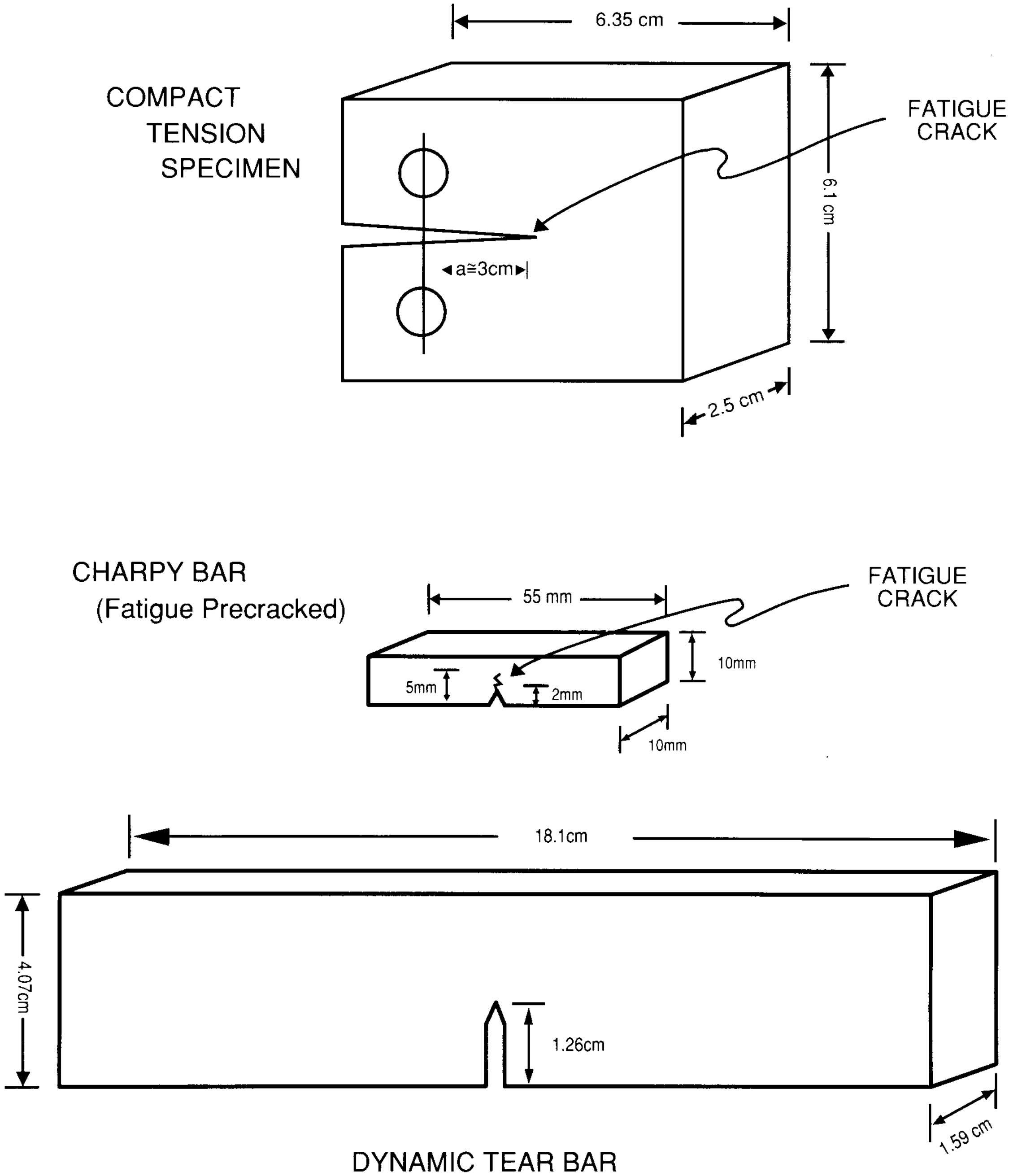


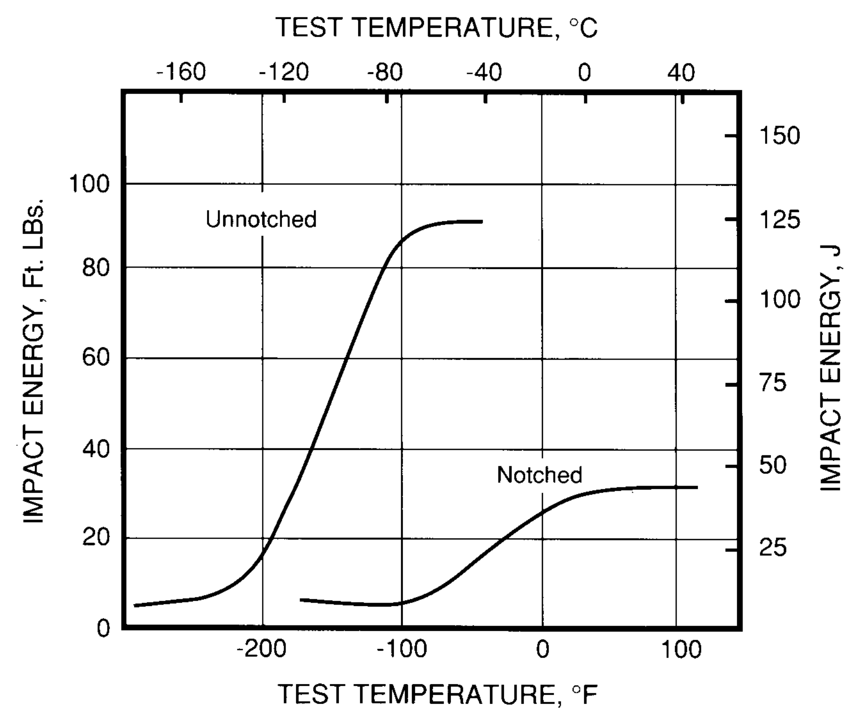
Figure 3.38 **Examples of specimens used for Charpy, dynamic tear and fracture toughness testing.**

according to appearance and absorbed energy, with a Nil-Ductility-Transition (NDT) temperature quoted to indicate the change from brittle to ductile behaviour. In addition to transition temperature, upper shelf energies were quoted to define toughness in the ductile fracture region.

Fracture Testing

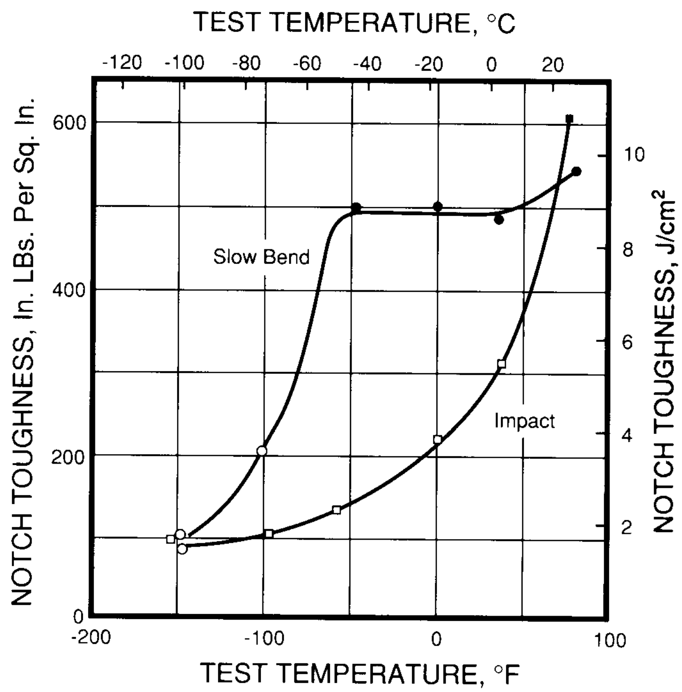
The Charpy test has been used for many years to characterize both the transition temperature and fracture energy for Ductile Iron, and a large body of Charpy impact energy data has been accumulated. The Charpy test is a dynamic fracture test in which a notched (see Figure 3.38) or unnotched test piece is struck an impact blow by a swinging pendulum. The effect of the notch on the fracture behaviour of ferritic Ductile Iron is shown in Figure 3.39. The shape of the notch is also important and must be considered. "V" shaped notches being more severe and producing lower strengths than "U" notches. The complex, triaxial stress state and increased strain rate at the root of the notch combine to restrict plastic deformation, increasing the transition temperature by 110 °F (60 °C) and reducing the upper shelf energy by 75 per cent. The effect of strain rate on fracture behaviour is illustrated in Figure 3.40, in which the results of dynamic (impact) tests of pre-cracked, notched Charpy bars are compared to quasi-static (slow bend) test results. The increased loading rate of the impact test produced a 115 °F (64 °C) increase in the transition temperature. Figures 3.39 and 3.40 highlight the sensitivity of fracture behaviour to test conditions and emphasize the strain rate sensitivity of Ductile Iron.

Figure 3.39



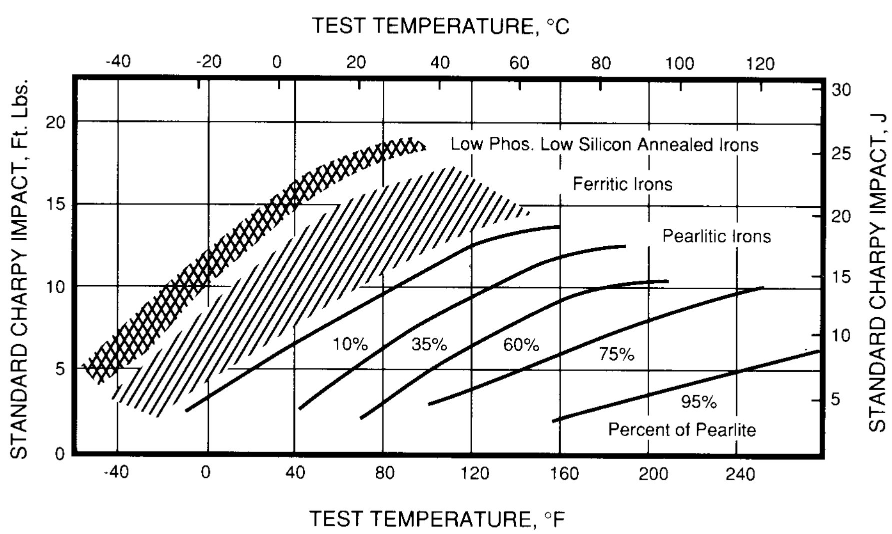
Charpy impact curves for v-notched and unnotched ferritic Ductile Iron.

Figure 3.40



Effect of loading rate on impact energy for precracked, v-notched Charpy specimens.

Figure 3.41



Effect of matrix microstructure on impact energy for v-notched Charpy specimens.

Recent advances in fracture mechanics have resulted in the use of the Dynamic Tear Test, ASTM E604, and the fracture toughness tests, ASTM E399 and ASTM E813,(see Figure 3.38 for sample geometry) to determine crack propagation properties, which are considered more relevant to the assessment of the flaw tolerance of a stressed component. This section will use data obtained from standard and modified Charpy tests and from dynamic tear and fracture toughness tests to characterize the fracture behaviour of Ductile Iron. The large body of standard Charpy data will be used to illustrate the relative effects of microstructure, composition, heat treatment and stress environment on fracture behaviour. Data from the other tests are offered to provide the designer with the quantitative information required to make materials selection and component design decisions. Again, fracture toughness information is more relevant and Ductile Iron compares well with steel in toughness levels where it is not shown to be as good with Charpy data.

Impact Properties
Effect of Microstructure

The impact properties of Ductile Iron are influenced significantly by matrix microstructure. As shown in Figure 3.41, Ductile Irons with annealed ferritic matrices exhibit the lowest ductile-to-brittle transition temperature and highest upper shelf energy. Special, annealed or subcritically annealed ferritic Ductile Irons with tensile strengths at or below 60,000 psi (414 MPa) are normally specified when very high notch ductility and good low temperature toughness are required. These irons have v-notched Charpy impact transition temperatures in the range 0 °C to – 60 °C (32 °F to – 76 °F), depending on heat treatment, composition and graphite properties (see Figures 3.42-3.46). These materials normally exhibit upper shelf energies in the range 16-24 Joules (12-18 ft lbf) with room temperature values in excess of 16 Joules (12 ft lbf).

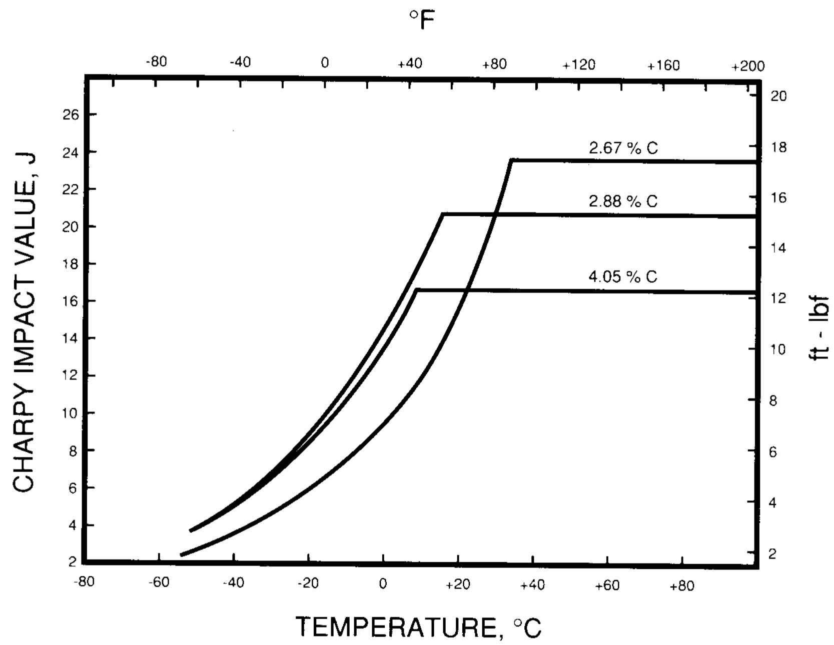
As-cast ferritic grades, and those with increasing percentages of pearlite, have increasingly higher transition temperatures and lower upper shelf energies. Generally, pearlitic grades of Ductile Iron are used because of their higher strengths in applications requiring only limited ductility and toughness and are generally not recommended for use in low temperature applications requiring impact resistance. However, in spite of apparently poor low temperature toughness, hundreds of ASTM Grade 100-70-03 gears have performed without problems in oilfield pumps operating at subzero temperatures in northern climates. Quenched and tempered martensitic Ductile Irons generally exhibit a combination of strength and low temperature toughness (see Figure 3.44) that is superior to those of pearlitic grades.

Effect of Composition

Carbon

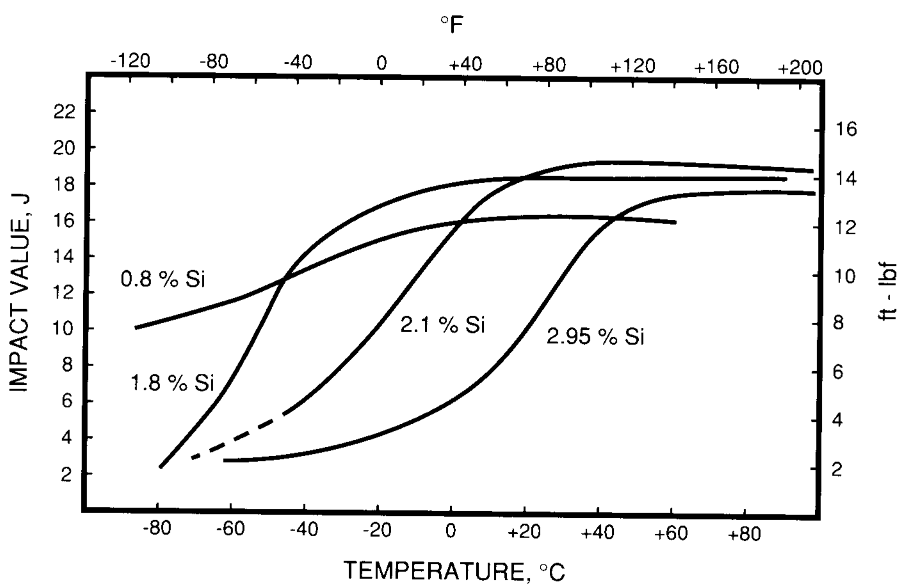
In addition to influencing microstructural characteristics such as ferrite: pearlite ratio and carbide content, composition also affects the fracture behaviour of annealed ferritic Ductile Iron. The influence of carbon content on notched impact properties is primarily on the upper shelf energy, which decreases with increasing carbon content, as shown in Figure 3.42. The influence of carbon in this region, in which fracture

Figure 3.42



Effect of carbon content on the v-notched Charpy energy of ferritic Ductile Iron.

Figure 3.43



Influence of silicon content on the v-notched Charpy energy of ferritic Ductile Iron.

occurs by the formation of voids on graphite nodules, and the growth and coalescence of these voids, is to increase the number and size of nodules. Increasing carbon content thus reduces the plastic deformation required to grow and coalesce voids, resulting in reduced plastic fracture energy. This relationship between carbon content and limiting plastic fracture strain is consistent with the observation that elongation and other indicators of ductility in ferritic Ductile Iron increase with decreasing carbon content. (Fluidity, microstructural and shrinkage considerations normally require carbon levels above 3.2 per cent.)

Silicon

The strong influence of silicon on the ductile-brittle transition temperature of ferritic Ductile Iron is shown in Figure 3.43. This Figure indicates that, to optimize low temperature toughness, silicon contents should be kept as low as possible. The successful production of as-cast carbide-free, low silicon Ductile Iron with a fully ferritic matrix requires high purity charge materials to minimize pearlite and carbide forming elements, controlled melting, holding and treating practices, and highly effective inoculation to maximize nodule count. The reduction in silicon level reduces both the yield and tensile strengths of the ferritic iron, and an offsetting addition of a less harmful ferrite strengthening element (such as nickel) is then needed to meet strength requirements. As with carbon, other considerations, especially microstructural control, require final silicon levels above 2 per cent.

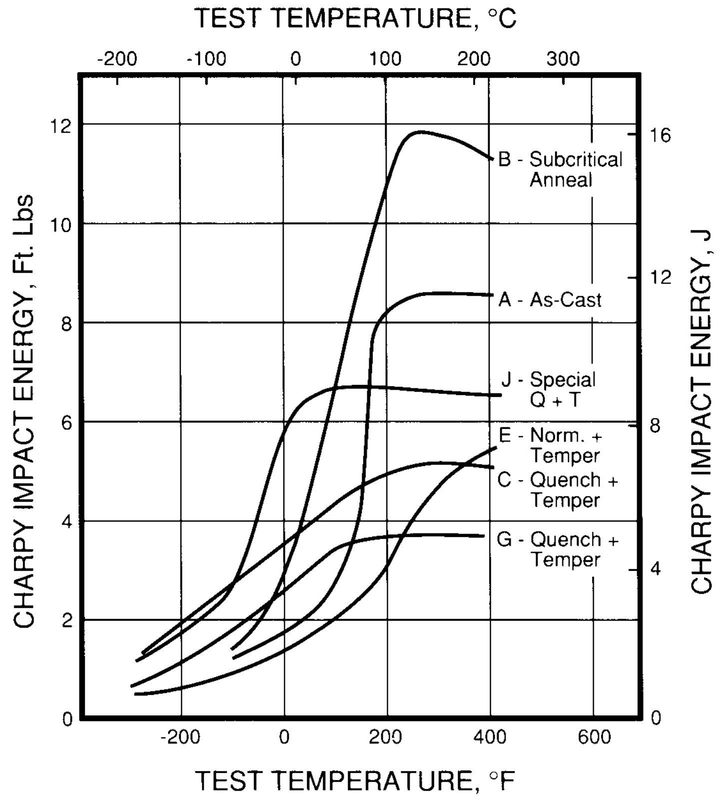
Manganese
Copper
Nickel
Phosphorus

Manganese, copper and nickel are some of the other major elements normally found in ferritic Ductile Iron. Manganese levels are kept low through dilution with high purity pig iron to avoid pearlite and carbide formation. The use of copper to strengthen low-silicon ferrite is precluded by its strong effect on transition temperature. A 1 per cent addition of copper will raise the transition temperature by 45 °C (80 °F). Nickel, which increases the transition temperature by only 10 °C (20 °F) for a 1 per cent addition, is the preferred ferrite strengthener for ferritic Ductile Irons requiring maximum low temperature toughness. Depending on its level, the pearlite stabilizing effect of the nickel may require an annealing treatment to ensure a fully ferritic matrix. Phosphorus, an impurity element in Ductile Iron, has a strong embrittling effect at levels as low as 0.02 per cent, see Figure 3.49.

Effect of Heat Treatment

Heat treatment, through its influence on microstructure, has a strong effect on impact properties. Figure 3.44 shows the effect on notched Charpy impact properties of the heat treatments described in Table 3.4. Subcritical annealing produced a fully ferritic, low strength structure with the highest upper shelf energy and the second lowest transition temperature. A special quench and temper treatment in which a low austenitizing temperature was used to produce a low carbon austenite, which was subsequently quenched and tempered, produced a superior combination of high strength and the low transition temperature. The normalized and tempered structure produced the poorest impact properties. When considering a material to obtain the best impact properties

Figure 3.44



Influence of heat treatment on the v-notched Charpy behaviour of Ductile Iron.

Table 3.4

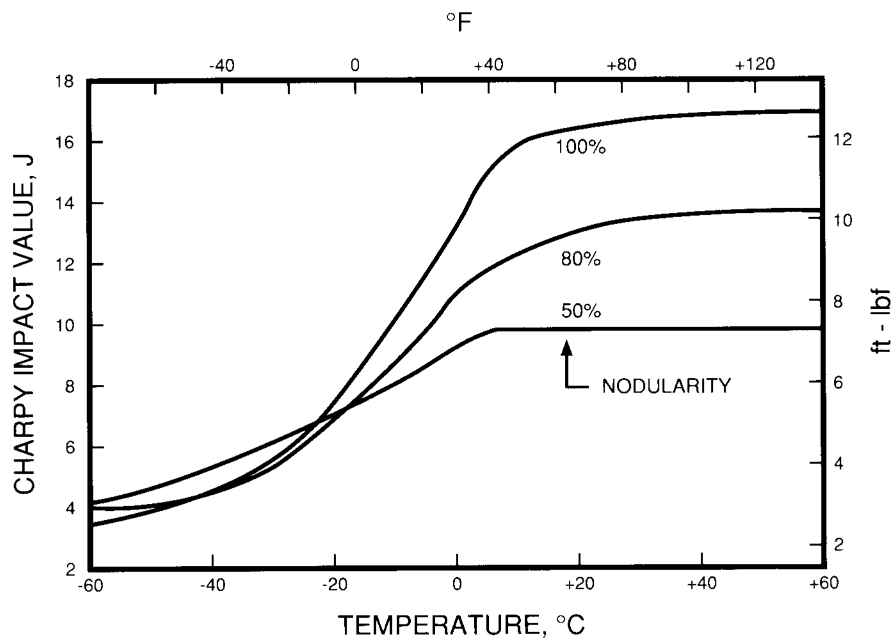
Sample*	Heat Treatment	Tensile Strength psi	Tensile Strength MPa	Yield Strength psi	Yield Strength MPa	Elongation % in 2"	Hardness Rc
A	As-Cast	77,750	*536*	48,650	*336*	13.0	7
B	Annealed at 1300 F, *700 C*	62,450	*431*	45,850	*316*	23.6	1
C	1650 F, *900 C* Quench 1250 F, *680 C* Temper	92,075	*635*	76,450	*527*	8.8	19
E	1650 F, *900 C* Normalize 1175 F, *635 C* Temper	112,950	*779*	68,100	*470*	8.2	21
J	1580 F, *860 C* Quench 1200 F, *650 C* Temper	108,450	*748*	84,200	*581*	9.4	18
G	1580 F, *860 C* Quench 900 F, *480 C* Temper	152,370	*1,051*	114,850	*792*	4.1	29

* Analysis: 3.65% TC, 2.48% Si, 0.52% Mn, 0.065% P, 0.78% Ni, 0.08% Cr, 0.15% Cu

Summary of heat treatments and tensile properties for the Ductile Iron samples used in Figure 3.44.

produced by the various heat treatments, it should be noted that the composition of the Ductile Iron used in the tests (shown at the bottom of Table 3.4) is **"very poor"**. This material has high levels of phosphorus, silicon, chromium and manganese. The impact strength would be higher if the chemistry was improved.

Figure 3.45

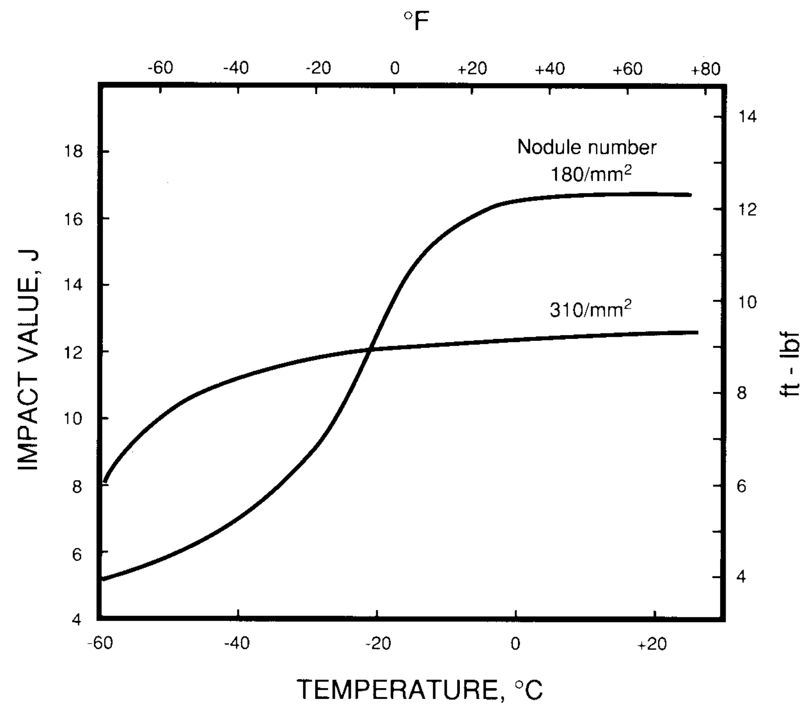


Influence of graphite nodularity on the Charpy fracture properties of v-notched samples of ferritic Ductile Iron.

Effect of Graphite Characteristics

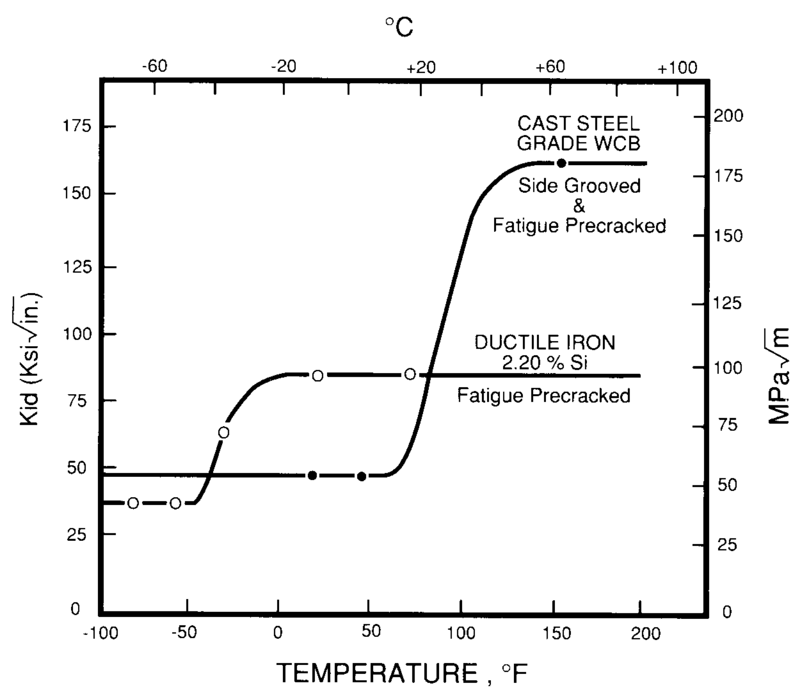
Impact properties of ferritic Ductile Irons are influenced by both nodularity and nodule count. In Figure 3.45, notched Charpy energies in the upper shelf region decrease significantly with decreasing nodularity. Transition temperatures and lower shelf energies are not affected by graphite shape. Nodule count also has a significant influence on both upper shelf energy and transition temperature. Increasing the nodule count from $180/mm^2$ to $310/mm^2$ (Figure 3.46) causes a decrease in transition temperature of 40 °C (70 °F) and a 25 per cent decrease in upper shelf energy. The use of late inoculation to produce higher and more consistent nodule counts presents both the designer and foundryman with a dilema. Should upper shelf energies be sacrificed in order to obtain increased low temperature impact properties? The Charpy test is too imprecise and potentially erroneous to answer this question. Fracture

Figure 3.46



Effect of nodule count on the v-notched Charpy impact properties of ferritic Ductile Iron.

Figure 3.47



Dynamic stress intensity factors K_{1D} for cast steel and ferritic Ductile Iron determined by a modified Charpy test.

SECTION III

mechanics may be required to determine the true contribution of nodule count to fracture toughness. Figure 3.48 suggests that increasing the nodule count from a low level, may improve fracture toughness when Ductile Irons exhibit brittle fracture behaviour.

Modified Charpy Test Results

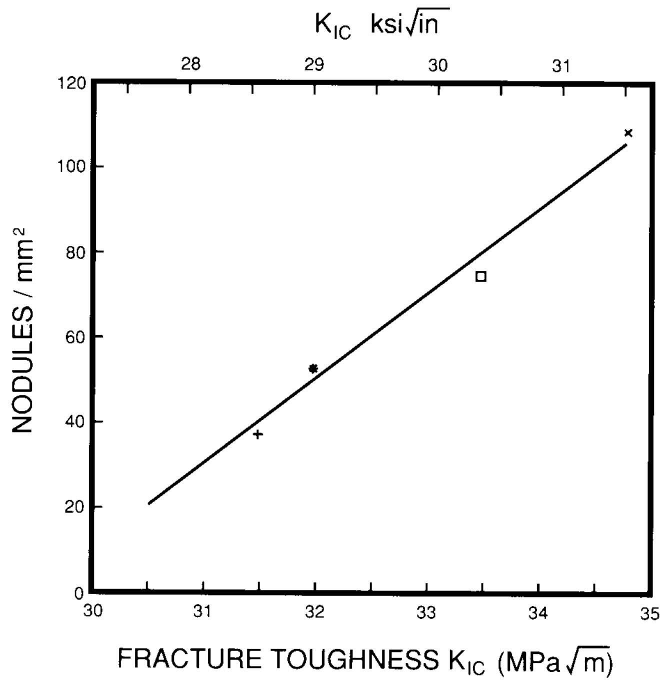
Although tensile data indicate that Ductile Iron has strength and ductility similar to cast steels, standard notched Charpy tests suggest that Ductile Iron has significantly lower fracture toughness, with energy values in the range 16-24 Joules (12-18 ft lbf) compared to cast steels with 60-75 Joules (44-55 ft lbf). Before Charpy data is used to disqualify Ductile Iron from critical applications because of its apparently inferior toughness, the following shortcomings of the Charpy test should be considered in the light of current fracture mechanics information to determine toughness. First, fracture mechanics samples are precracked, while Charpy notches are relatively blunt. As a result, fracture mechanics tests measure resistance to crack propagation, while Charpy tests measure both initiation and propagation. Second, fracture toughness tests are conducted under quasi-static stress conditions while the Charpy test involves impact loading. Finally, fracture mechanics test samples are large enough to produce plane strain conditions, while the Charpy test involves plane stress, a fact clearly confirmed by the shear lips on fractured steel Charpy samples tested in the upper shelf region.

SECTION III

The formation of shear lips is the underlying cause of the significant difference between the Charpy behaviour of Ductile Iron and cast steel. The shear lips developed by the steel are responsible for a considerable fraction of its upper shelf energy. Due to the strain-limiting nature of the coalescence of voids initiated on graphite nodules, Ductile Iron does not exhibit shear lip formation under any conditions. As a result, when tested under the ''similar'' plane stress conditions present in the Charpy test, the shear lip formation of steel produces a significantly higher upper shelf fracture energy than Ductile Iron. Under plane strain conditions that could be expected in many component failures, the ''shear lip advantage'' of steel would be absent, with dramatically lower fracture toughness.

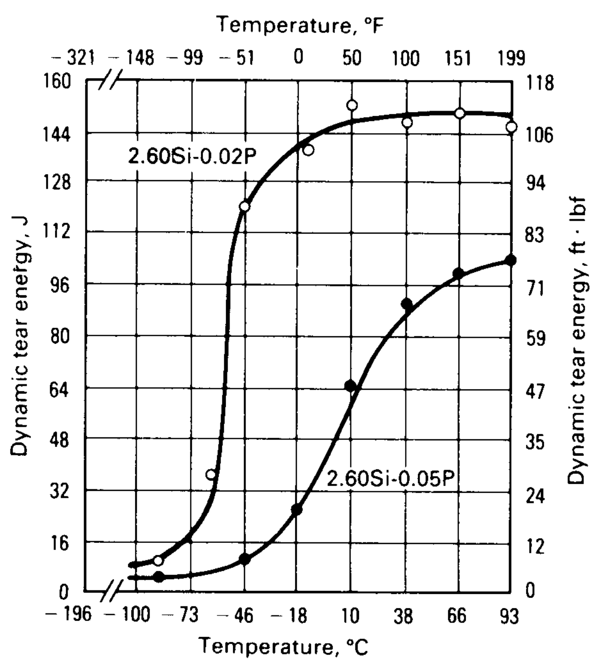
To eliminate the differences in upper shelf fracture mode between cast steel and ferritic Ductile Iron, the Charpy test was modified, using precracked and side- grooved samples to provide plane strain conditions at the initiation of crack growth. Using the J-integral method, the dynamic stress intensity factor K_{ID} was calculated for both materials over a temperature range including both brittle and ductile fracture modes. Figure 3.47 shows that the fracture toughness of cast steel was superior to that of ferritic Ductile Iron at temperatures above 90 °F (32 °C) but that the superiority was much less than that suggested by the Charpy test. Due to a much lower ductile-to-brittle transition temperature, Ductile Iron exhibited superior fracture toughness below 90 °F (32 °C).

Figure 3.48



Relationship between nodule count and critical stress intensity factor K_{1C} for pearlitic Ductile Iron at room temperature.

Figure 3.49

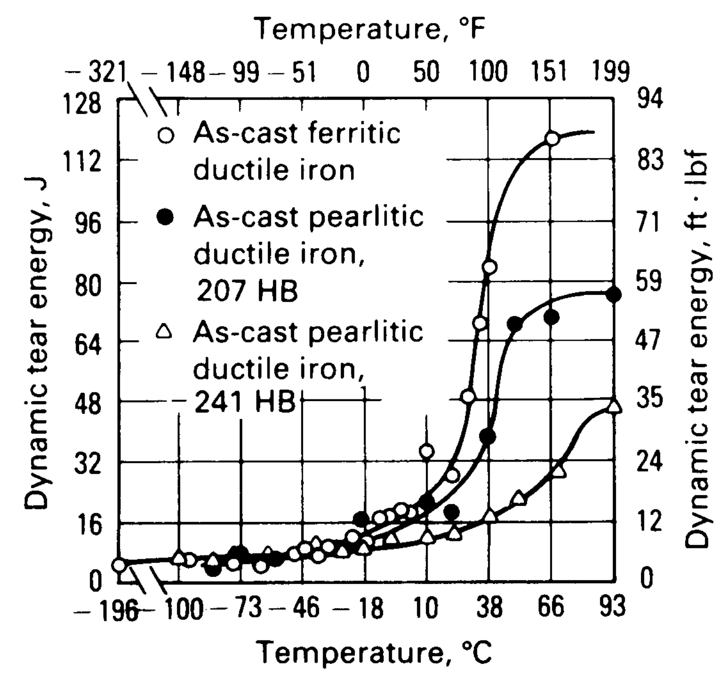


Dynamic tear data showing effect of phosphorus on impact fracture behaviour.

Figure 3.47 indicates that the fracture toughness of good quality ferritic Ductile Iron is excellent to temperatures as low as -80 °F (-62 °C), giving a K_{ID} of 37.5 ksi$\sqrt{in}$. (41 MPa$\sqrt{m}$), which corresponds to a critical flaw size of 0.5 in. (1.25 cm) for a design stress equal to the yield stress, applied under static fracture conditions. Above 0 °F (-18 °C), the K_{ID} is 80 ksi$\sqrt{in}$. (87 MPa$\sqrt{m}$) giving a critical flaw size of 1.5 in. (3.75 cm). Both flaw sizes can be detected and prevented by the quality assurance and production procedures practiced by competent Ductile Iron foundries. Assuming such flaws can be avoided, ferritic Ductile Iron can be considered sufficiently tough to resist unstable crack propagation at temperatures as low as -80 °F (-62 °C).

Figure 3.48 illustrates the relationship between fracture toughness and nodule count for pearlitic Ductile Iron tested at room temperature. This level of fracture toughness, at a temperature well below the transition temperature for pearlitic irons, (see Fig. 3.41) indicates that these irons are tougher than indicated by the notched Charpy test and have good flaw tolerance at temperatures at which they are labelled "brittle" by the Charpy test. The relationship between fracture toughness and nodularity indicates that the nodules are playing a role in determining fracture toughness, possibly through the relaxation of triaxial stresses through void formation at the crack tip.

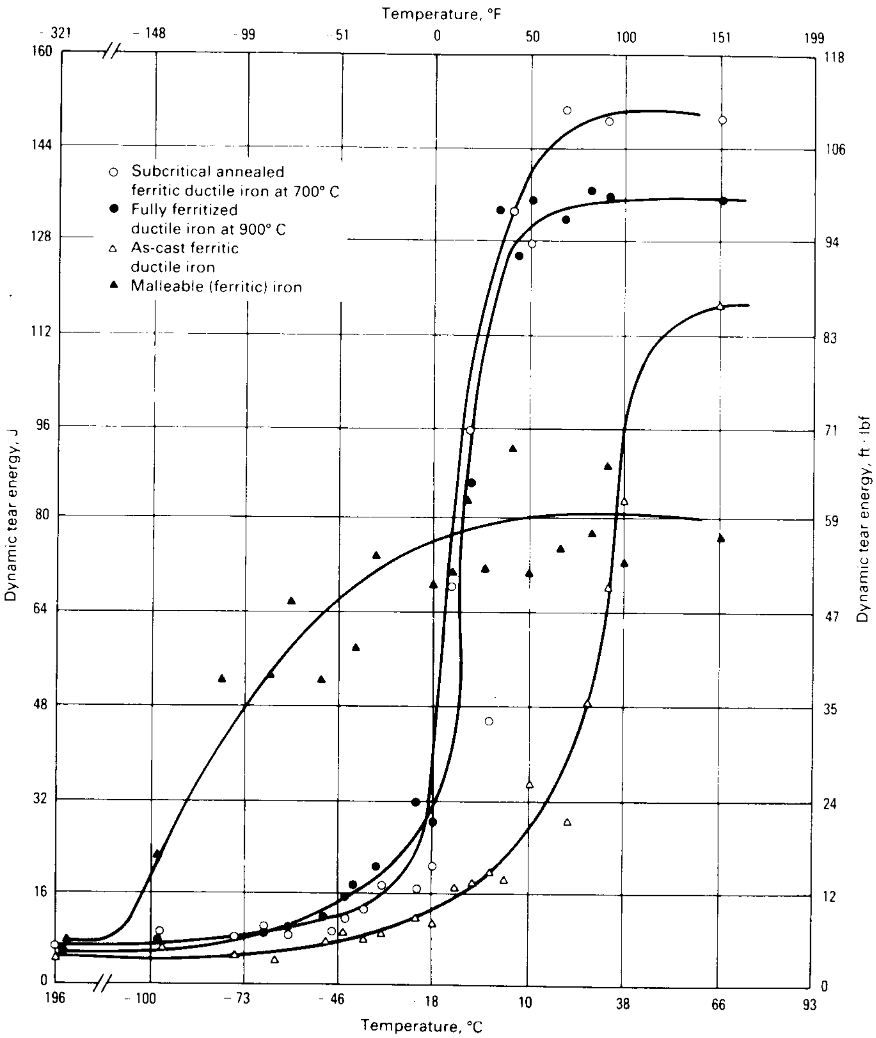
Figure 3.50



Dynamic tear data for as-cast ferritic and pearlitic Ductile Irons.

SECTION III

Figure 3.51



Dynamic tear data for four ferritic cast irons.

Dynamic Tear Testing

The dynamic tear test, an accepted ASTM fracture test method, overcomes many of the shortcomings of the Charpy test and is cheaper and more suitable than plane strain fracture toughness testing for production testing of ferrous castings. This test has become widely accepted in the automotive industry and has been made mandatory for the characterization of the fracture properties of castings used in critical applications. To ensure validity of test results, the dynamic tear specimens are cast to size in the foundry and tested full size to replicate performance of an actual casting. Figures 3.49-3.51 illustrate dynamic tear behaviour for as-cast ferritic and pearlitic, and annealed ferritic Ductile Irons respectively. When compared to similar Charpy data in Figure 3.41, the dynamic tear data in Figure 3.50 reveals a slightly higher transition temperature for the ferritic sample but significantly lower transition temperatures for the pearlitic grades. Figure 3.49 is noteworthy for two features: the low transition temperature of the low phosphorus, annealed ferritic iron, and the significant increase in transition temperature and reduction in upper shelf energy produced by an increase in phosphorus content to 0.05 per cent. Figure 3.51 compares the dynamic tear data for four ferritic cast irons. A full, ferritizing anneal reduces the fracture transition temperature and increases the upper shelf energy of Ductile Iron, compared to an as-cast ferritic structure. The use of a subcritical annealing instead of a normal full ferritizing treatment resulted in a similar transition temperature, but a higher upper shelf energy. In addition to slightly better impact properties, a subcritical anneal also produces improved fatigue strength.

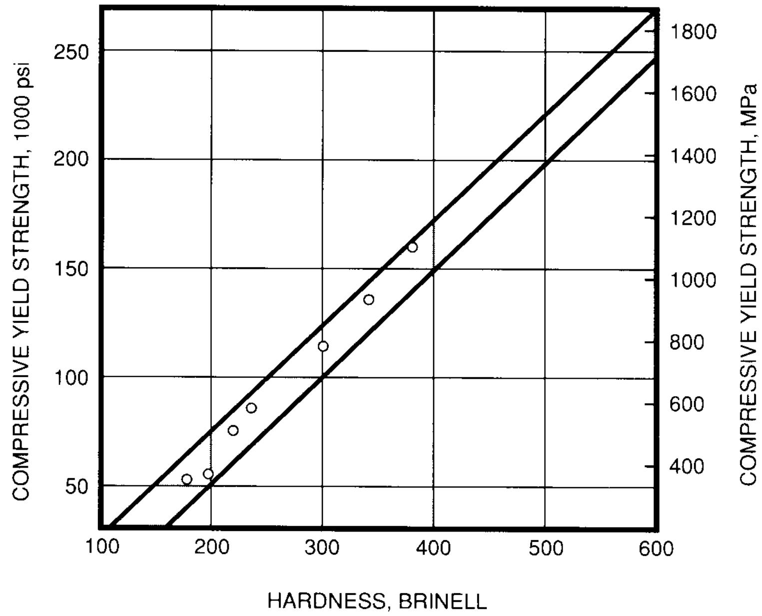
Temper Embrittlement

Temper embrittlement, as found in certain quenched and tempered steels, may also occur in similarly treated Ductile Irons with susceptible compositions. This form of embrittlement, which does not affect normal tensile properties but causes significant reductions in fracture toughness, can occur in Ductile Irons containing high levels of silicon and phosphorus which have been tempered in the range 650-1100 °F (350-600 °C) and cooled slowly after tempering. Although normally associated with tempered martensitic matrices, temper embrittlement can also occur if the matrix is tempered to the fully ferritic condition. Temper embrittlement can be prevented by keeping silicon and phosphorus levels low, additing up to 0.15 per cent molybdenum and avoiding the embrittling heat treating conditions.

Galvanizing Embrittlement

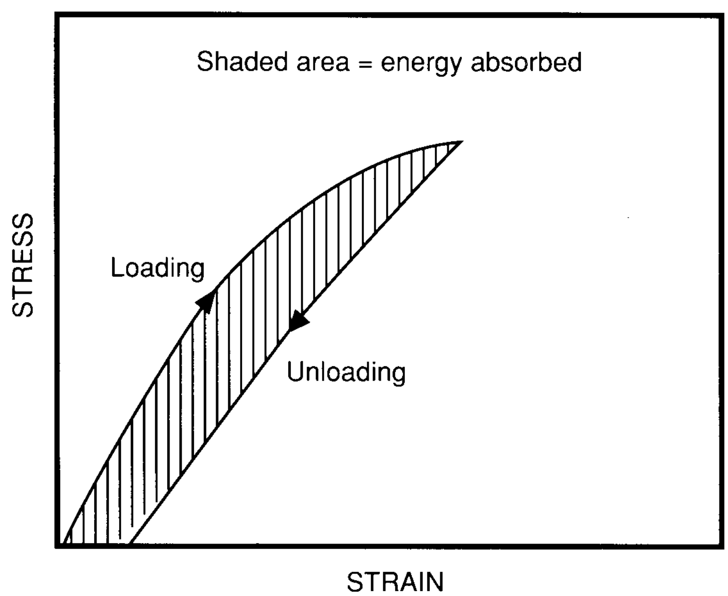
This form of embrittlement, named because it may be found in certain galvanized Ductile Iron and Malleable Iron castings, does not involve zinc and the galvanizing process directly but is caused in castings with relatively high silicon and phosphorus levels by the thermal environment created during galvanizing. For example, an annealed ferritic Ductile Iron of susceptible composition will be embrittled by quenching or rapid cooling after galvanizing in the temperature range 650-950 °F (350-500 °C). Although galvanizing embrittlement and temper embrit-

Figure 3.52



Relationship between hardness (BHN) and compressive yield stress.

Figure 3.53



Energy absorption due to non-elastic behaviour during cyclic stressing.

tlement are both related to high silicon and phosphorus levels, they differ in other, important respects. Galvanizing embrittlement normally occurs in annealed ferritic castings and is caused by rapid cooling from the embrittling temperature range, while temper embrittlement occurs in quenched and tempered castings and is caused by slow cooling.

OTHER MECHANICAL PROPERTIES

Modulus of Rigidity

The Modulus of Rigidity, or Modulus of Elasticity in Torsion, is the ratio of shear stress to shear strain. The Modulus of Rigidity and Modulus of Elasticity are related by the equation:

$$E = 2G(1 + v)$$
$$= 2.55G$$

where: E = Modulus of Elasticity,
G = Modulus of Rigidity, and
v = Poisson's Ratio.

Compressive Properties

The 0.2% compressive yield strength can be up to 20% higher than the tensile yield strength measured at the same offset. The relationship between the compressive yield strength and Brinell hardness is shown in Figure 3.52. The proportional limit in compression is a slightly higher proportion of the compressive yield strength and does not vary significantly between grades. A suitable estimate of the proportional limit in compression is obtained by using 75% of the 0.2% compressive yield strength for all grades of conventional Ductile Iron.

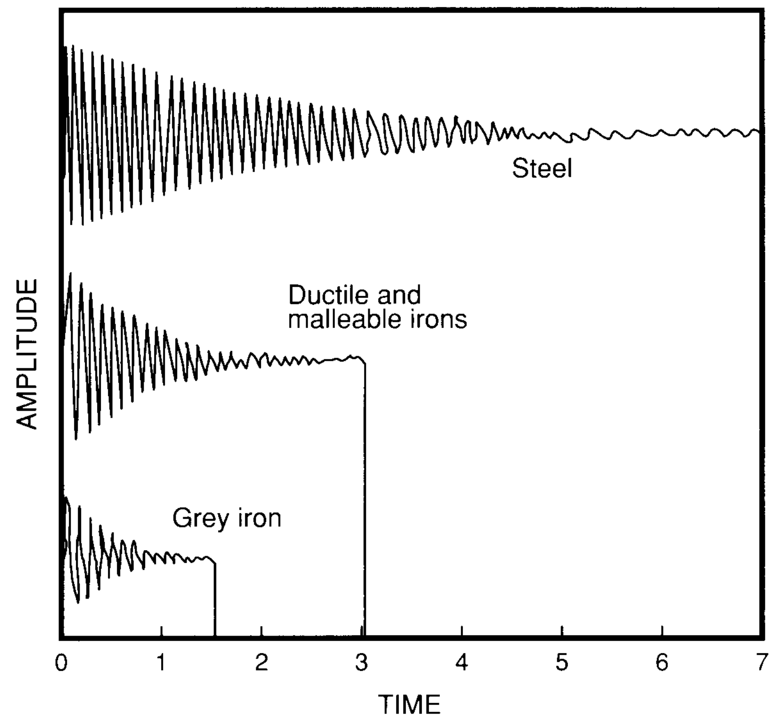
Torsional Properties

The ultimate strength in shear or torsion is generally considered to be about 90% of the tensile strength. However, there is a scarcity of accurate shear strength values in materials such as Ductile Iron that show some ductility because in a double shear test it is very difficult to avoid bending. Data on the proportional limit and yield stress in torsion are more reliable, with torsional values being about 75% of the respective tensile values.

Damping Capacity

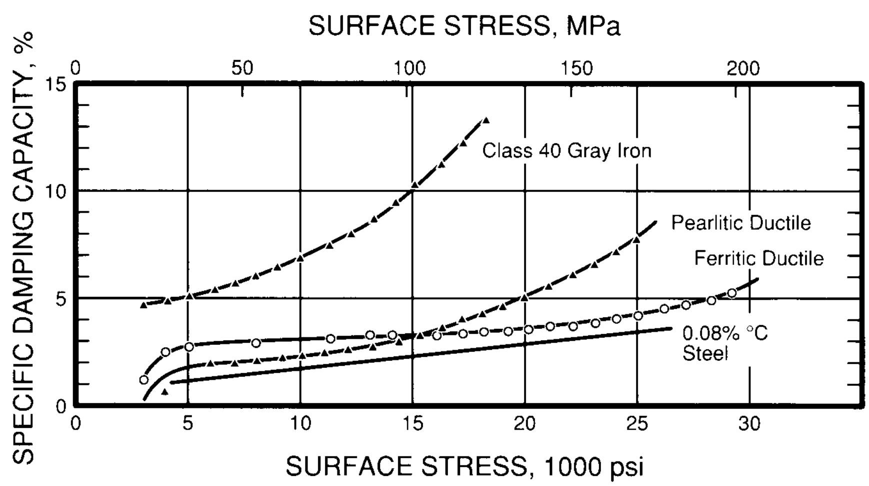
Damping capacity plays a significant role in modern engineering design. High damping capacity reduces the noise and subsonic vibrations emitted by machinery components which are subjected to cyclic stressing. Combustion engines are quieter and transmit less vibration to attached components, machine tools are less noisy and produce a smoother surface finish. The only disadvantages of damping are the additional frictional losses and related heat build-up that result from the absorption of vibrational energy by a material with high damping capacity.

Figure 3.54



Relative damping behaviours of steel, Ductile and Malleable Irons and Gray Iron.

Figure 3.55



Variation of damping capacity with surface stress for Gray Iron, ferritic and pearlitic Ductile Iron and steel.

SECTION III

A more profound significance of damping capacity is in its contribution to fatigue resistance. Two materials with the same measured fatigue resistance but with different damping capacities will perform differently in service. In most actual service environments (as opposed to fatigue testing) vibrations occur intermittently and with varying frequency and amplitude. A rapid damping of these vibrations reduces the length of time during which the stress amplitude may reach or exceed the fatigue limit. As a result, high damping capacity enhances fatigue resistance.

Damping Mechanism

Damping is the ability of a material to absorb vibrational energy by some form of internal friction. In metals the primary damping mechanism is localized non-elastic (microplastic) behaviour. Under cyclic loading conditions this microplastic behaviour, shown in Figure 3.53, produces a hysteresis loop whose area is proportional to the energy absorbed during each cycle (vibration). The low stress behaviours of Gray Iron, Ductile Iron and mild steel, see Figure 3.3, indicate their relative damping capacities. Gray Iron, which exhibits non-elastic behaviour at very low stresses, has the highest damping capacity, while steel, which behaves elastically up to its yield point, has the lowest damping capacity. Figure 3.54 schematically illustrates the relative damping capacities of these materials through a comparison of reduction in vibrational amplitude with time. The relative decreases in vibrational amplitude illustrated in this Figure can vary as follows for ferrous materials:

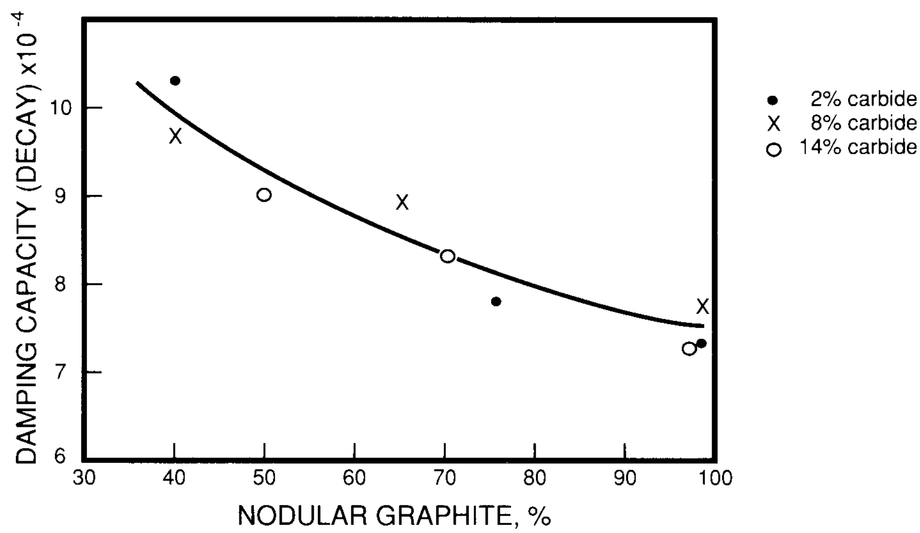
Material	Relative Decrease in Amplitude Per Cycle
Carbon Steel	1 - 2
Malleable Iron	3 - 6
Ductile Iron	3 - 9
High Strength Gray Iron	4 - 9
Low Strength Gray Iron	20 - 60
Hypereutectic Gray Iron	>100

Effects of microstructure

In addition to the general variations related to different types of material, damping capacity is also affected within a family of materials by applied stress state and microstructure. Figure 3.55 shows the variation in damping capacity with surface stress for Gray Iron, low carbon steel and ferritic and pearlitic Ductile Iron. Figures 3.56 and 3.57 illustrate the influence of microstructure on damping behaviour of Ductile Iron. As would be expected from the relative damping capacities of Gray and Ductile Irons, as the percentage of spherical graphite decreases (and the amount of flake-like graphite increases), damping capacity increases significantly (see Figure 3.56). This Figure also shows that damping ca-

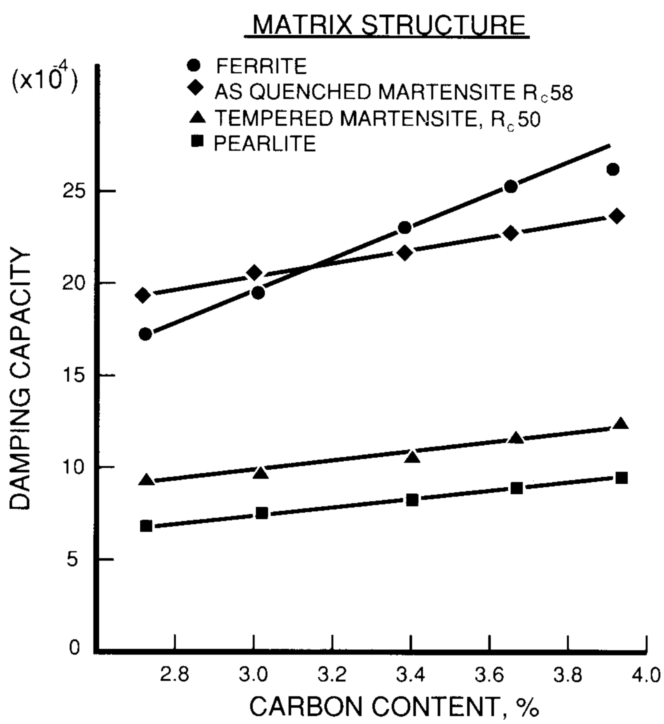
SECTION III

Figure 3.56



Effect of nodularity on damping capacity.

Figure 3.57



Effect of carbon content and matrix structure on damping capacity.

pacity is not affected strongly by carbide contents up to 14 volume per cent. Figure 3.57 shows that damping capacity generally decreases with increased matrix hardness and increases with carbon content. The only exception to the damping-hardness relationship is for as-quenched martensite, in which the internal stresses produced by the formation of martensite increase microplastic deformation and thus increase damping. As shown in Figure 3.55, ferritic and pearlitic Ductile Irons exhibit a transition in relative damping capacity as the applied stress is increased. At low stresses, the softer ferritic matrix has higher damping capacity, while at higher stresses, the damping capacity of the pearlitic matrix is greater.

PHYSICAL PROPERTIES

Density

The generally accepted value for the room temperature density of Ductile Iron is 7.1 g/cm^3. Density is affected primarily by the percentage of graphitized carbon, with densities varying from 6.8 g/cm^3 to 7.4 g/cm^3 for high carbon ferritic and low carbon pearlitic irons respectively. The density of a typical cast steel – 7.8 grams/cm^3 – is almost 10 per cent higher than that of Ductile Iron. The replacement of a steel casting or forging with a lighter Ductile Iron casting improves the component strength: weight ratio, reducing energy savings and lifetime costs, especially in reciprocating components such as automotive crankshafts.

Thermal Expansion

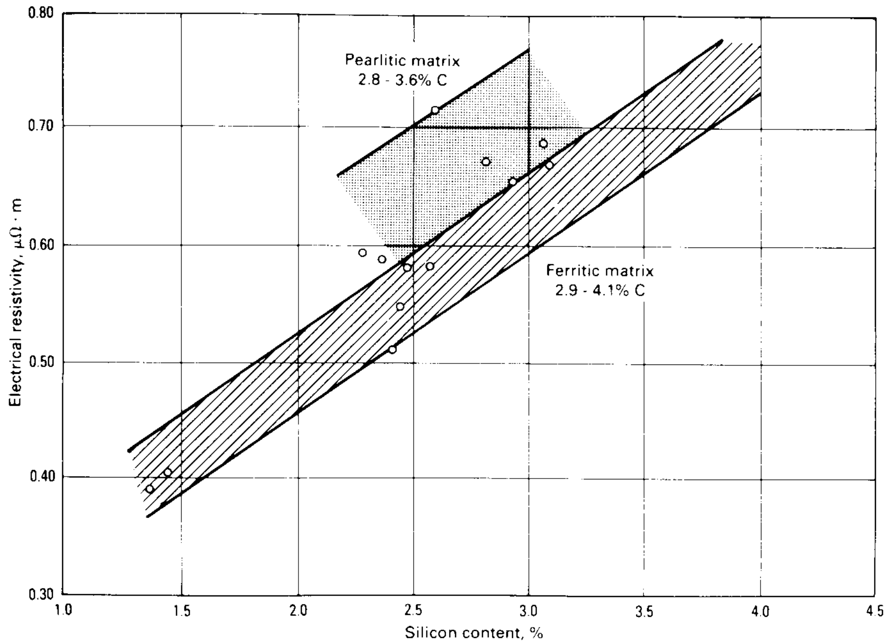
The coefficient of linear thermal expansion of Ductile Iron depends primarily on microstructure, although it is influenced to a minor extent by temperature and graphite structure. In unalloyed Ductile Iron, composition has only a slight influence on thermal expansion, but alloyed austenitic Ductile Irons can exhibit significantly different expansion behaviour, see Table 3.5.

Table 3.5

Temperature Range		Ferritic 60-45-10		Pearlitic 80-60-03		Austenitic 20-26% Ni	
°F	°C	10^{-6}/F	10^{-6}/C	10^{-6}/F	10^{-6}/C	10^{-6}/F	10^{-6}/C
68- 212	20-100	6.4	11.5	6.4	11.5		
68- 392	20-200	6.5-6.6	11.7-11.8	6.6-7.0	11.8-12.6	2.2-10.5	4-19
68- 572	20-300	—	—	7.0	12.6	—	—
68- 752	20-400	—	—	7.3	13.2	—	—
68- 932	20-500	—	—	7.4	13.4	—	—
68-1112	20-600	7.5	13.5	7.5	13.5	—	—
68-1292	20-700	—	—	7.7	13.8	—	—

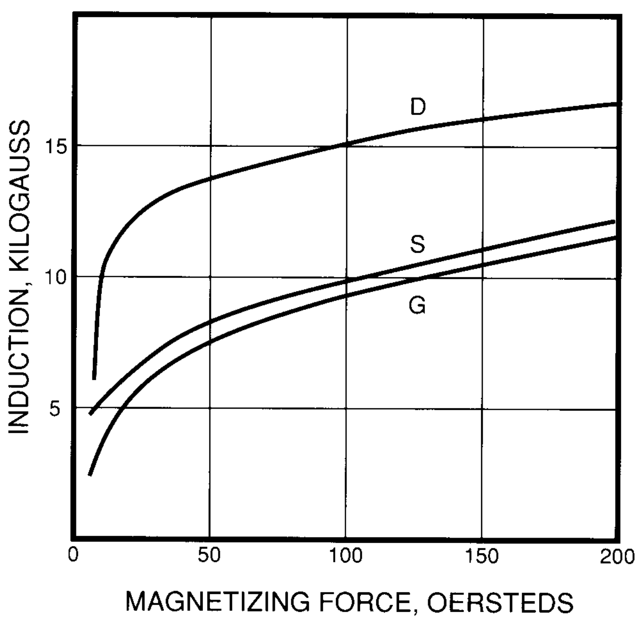
Effect of temperature on the coefficient of thermal expansion for different Ductile Irons.

Figure 3.58



Effect of matrix and silicon content on the electrical resistivity of Ductile Iron.

Figure 3.59



Magnetization curves for ferritic irons described in Table 3.6.

Thermal Conductivity

The thermal and electrical conductivity of Gray and Ductile Irons are influenced strongly by graphite morphology. The conductivity is higher in Gray Iron because of the semi-continuous nature of the graphite flakes. Because of the influence of flake graphite on the conductivity, the volume fraction of graphite plays an important role in Gray Iron, but not in Ductile Iron. In addition to graphite shape, microstructure, composition, and temperature also influence thermal conductivity. Ferritic Ductile Irons have a higher thermal conductivity than pearlitic grades, and quenched and tempered irons have values between those of ferritic and pearlitic irons. In the range 20-500 °C (68-930 °F), the thermal conductivity of ferritic grades is 36 W/m °K (250 Btu in./ft^2 h °F). Conductivity for pearlitic grades over the same temperature range is approximately 20 per cent less.

Specific Heat

Specific heat, the amount of energy required to increase the temperature of a unit mass of a body by one degree, generally increases with temperature, reaching a maximum whenever a phase transformation occurs. For unalloyed Ductile Iron, the specific heat varies with temperature as follows:

Temperature		Specific Heat	
°C	°F	J/kg °K	Btu/lb °F
20-200	70-390	461	0.110
20-300	70-570	494	0.118
20-400	70-750	507	0.121
20-500	70-930	515	0.123
20-600	70-1110	536	0.128
20-700	70-1290	603	0.144

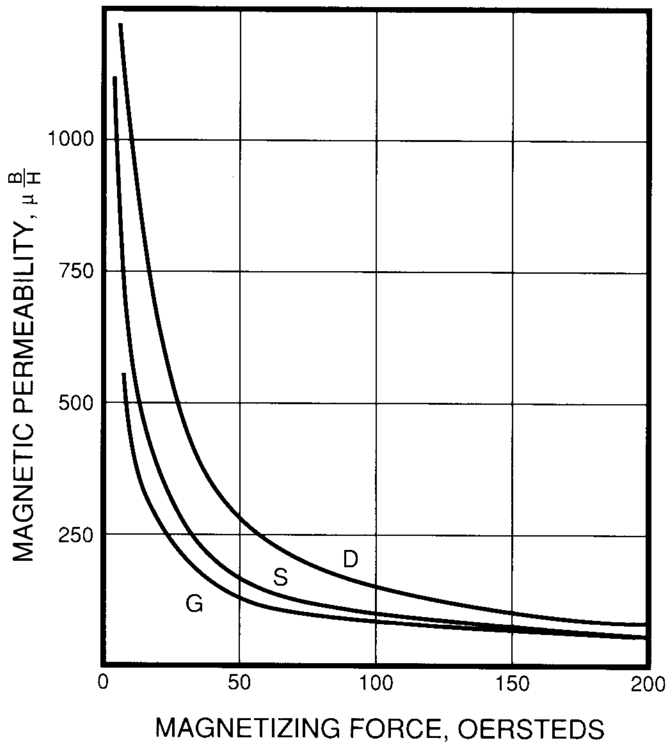
Electrical Resistivity

Ductile Irons, with discontinuous spherical graphite, have lower electrical resistivity than Gray Irons which have semi-continuous flake graphite. The primary elements effecting resistivity are silicon and nickel, both of which increase resistivity. The effects of matrix structure and silicon content on the electrical resistivity of Ductile Iron at room temperature are shown in Figure 3.58.

Magnetic Properties

The magnetic properties of Ductile Irons are determined mainly by their microstructures. The spheroidal shape of the graphite particles in Ductile Irons gives them higher induction and higher permeability than Gray Irons with a similar matrix. Ferritic Ductile Irons are magnetically softer than pearlitic grades – they have higher permeability and lower hysteresis loss. For maximum permeability and minimum hysteresis loss, ferritic, low phosphorus irons should be used. Magnetization and permeability curves are shown in Figures 3.59 and 3.60 for three ferritic cast irons. The magnetic and electrical properties of these irons are summarized in Table 3.6.

Figure 3.60



Magnetic permeability of the three ferritic irons in Table 3.6.

Table 3.6

Symbol Type of Iron	G Annealed Gray Iron	D Annealed Ductile	S Silal
Composition, %			
Total Carbon	3.71	3.55	2.66
Silicon	1.66	2.33	5.94
Manganese	0.30	0.30	53
Magnetizing Force			
25 Oersteds	8,200	14,200	8,900
50 Oersteds	8,900	14,800	9,600
100 Oersteds	9,900	15,600	10,500
150 Oersteds	11,000	16,200	—
Remanence			
Kilogauss	7.0	10.7	7.7
Cohesive Field			
Oersteds	2.5	3.0	3.4
Resistance			
Michrohm-cm.	90	52	180

Magnetic and electrical properties of the ferritic irons described in Figures 3.59 and 3.60.

Wear Resistance

Mechanical wear may be defined as surface deterioration and/or material loss caused by stresses arising from contact between the surfaces of two bodies. Wear is primarily mechanical in nature but chemical reactions may also be involved. Wear is a complex phenomenon and may involve one or more of the following mechanisms:

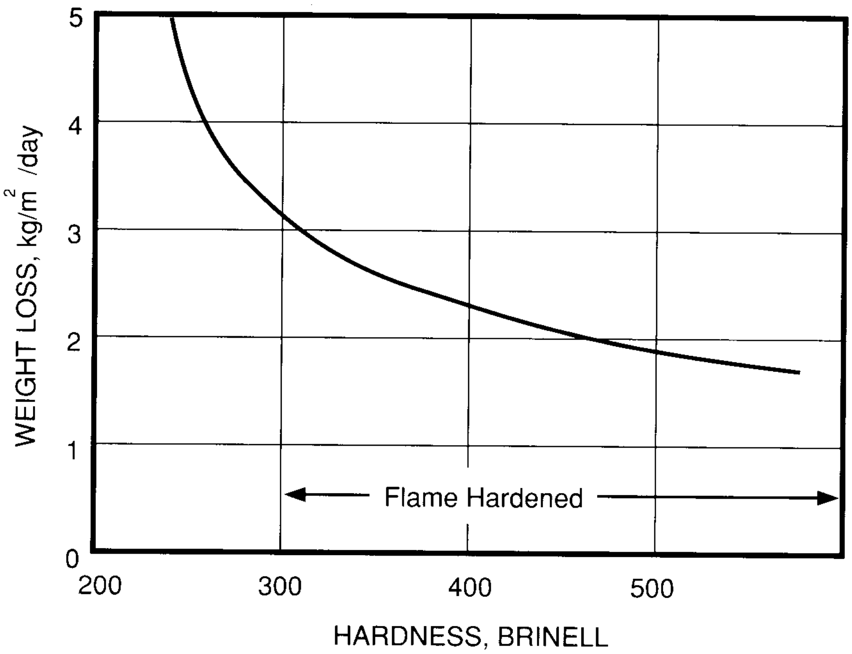
- abrasive wear caused by the removal of material from one body due to contact with a harder body,
- adhesive or frictional wear caused by the relative sliding contact of two bodies,
- fretting or fatigue wear resulting from cyclic stresses caused by the relative motion of two contacting bodies, and
- cavitation wear caused by the motion of fluid at high velocity across the surface of a body.

The complexity of wear phenomena and their dependence on both material properties and environment have precluded the use of a universal wear test to evaluate and compare the wear behaviour of different materials under different wear conditions. As a result, many tests have been developed for evaluating wear resistance, with each test applying to a specific set of conditions. Therefore, the discussion of wear resistance is limited to general, comparative statements and to some thoughts on how the microstructure of Ductile Irons affect their wear resistance.

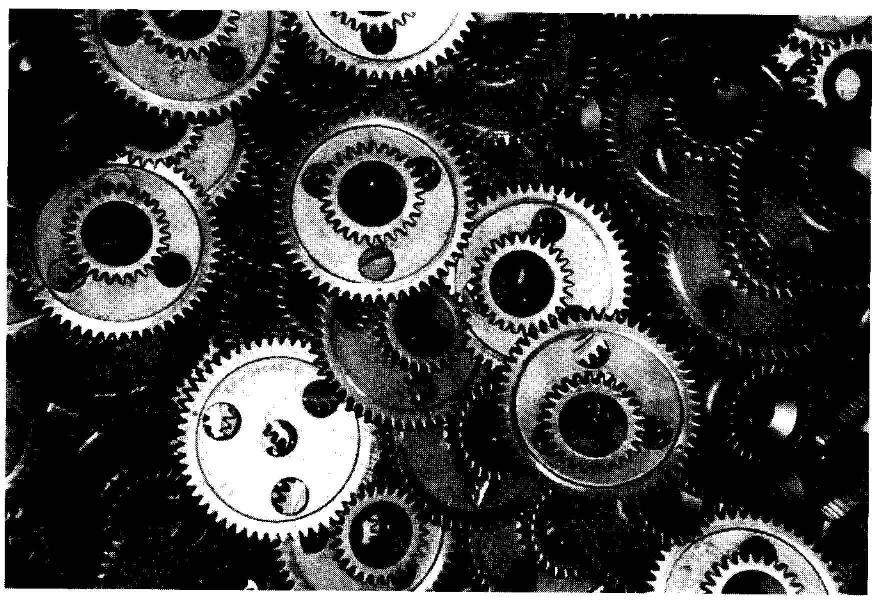
Cast irons have been recognized for many years as ideal materials for a wide range of wear applications, especially frictional wear under both dry and lubricated conditions. In dry wear, sufficient heat may be generated by the friction between the working surfaces to harden the individual surfaces or, in severe cases, fuse them together. Under these conditions the graphite particles in cast irons lubricate the surfaces, reducing friction and minimizing surface deterioration by overheating. Graphitic cast irons also perform well in lubricated sliding wear. The graphite particles on the wear surfaces act as reservoirs for oil and, under loads high enough to displace the oil film, the lubricating effect of the graphite itself provides galling resistance.

The wear resistance of Ductile Irons are determined primarily by their microstructures. The presence of 8-11 volume per cent graphite provides both the graphitic lubrication and oil retention essential to some wear applications. Pearlite, consisting of very hard lamellar carbide in a soft, ductile matrix of ferrite, exhibits good wear resistance under wear conditions involving both friction and moderate abrasion. Further improve-

Figure 3.61



Relationship between weight loss due to abrasive wear and hardness of flame hardened Ductile Iron.



ADI gears with as-cast teeth.

ments in resistance to abrasive wear may be obtained through alloying and/or heat treatment to produce a harder martensitic, austempered or bainitic matrix, Figure 3.61. Additional information on heat treatment and surface treatment can be found in Sections VII and IX.

Corrosion Resistance

Unalloyed Ductile Irons exhibit approximately the same corrosion resistance as Gray Iron and are superior to unalloyed steel, and even highly alloyed steels in certain environments. Corrosive environments degrade the performance of Ductile Iron in two ways: the embrittlement of monotonically stressed components described earlier in this section, and the loss of material and structural integrity caused by corrosive action alone. Corrosion can also play a significant role in abrasive wear resistance. Corrosion of Ductile Irons and other ferrous materials is a complex phenomenom and a detailed discussion of corrosion behaviour is beyond the scope of this section. The corrosion behaviour of alloyed Ductile Irons is discussed briefly in Section V. Data describing the general corrosion behaviour of Ductile Irons can be found in the following sources:

''Corrosion Data Survey'', National Association of Corrosion Engineers, Katy, Texas, 1974.

''Iron Castings Handbook'', Iron Castings Society, 1981.

SECTION III

REFERENCES

A Design Engineer's Digest of Ductile Iron, 5th Edition, 1983, QIT-Fer et Titane Inc., Montreal, Quebec, Canada.

BCIRA Broadsheet 157-2, ''Stress/strain behaviour of nodular and malleable cast irons,'' British Cast Iron Research Association, 1981.

B. V. Kovacs, ''Quality Control and Assurance by Sonic Resonance in Ductile Iron Castings,'' Transactions, American Foundrymen's Society, Vol. 85, 1977, pp 499-508.

B. V. Kovacs, ''On the Interaction of Acoustic Waves with SG Iron Castings.'' Transactions, American Foundrymen's Society, Vol 83, 1975, pp 497-502.

W. Siefer and K. Orths, ''Evaluation of Ductile Iron in Terms of Feasible Properties of the Material.'' Transactions, American Foundrymen's Society, Vol 78, 1970 pp 382-387.

D. L. Crews, ''Quality and Specifications of Ductile Iron.'' Transactions, American Foundrymen's Society, Vol 82, 1974, pp 223-228.

D. Venugopalan and A. Alagarsamy, ''Effects of Alloy Additions on the Microstructure and Mechanical Properties of Commercial Ductile Iron.'' Transactions, American Foundrymen's Society, Vol 98, 1990, Paper #90-122.

E. N. Pan, M. S. Lou and C. R. Loper Jr., ''Effects of Copper, Tin and Manganese on the Eutectoid Transformation of Graphitic Cast Irons.'' Transactions, American Foundrymen's Society, Vol 95, 1987, pp 819-840.

T. Levin, P.C. Rosenthal, C.R. Loper Jr. and R. Heine, "Tin and Copper in Ductile Iron." Transactions, American Foundrymen's Society, Vol 79, 1971, pp 493-514.

O. Okarafar and C. R. Loper, "The Effect of the Exposure to Water on the Tensile Properties of Ductile Cast Iron.", Transactions, American Foundrymen's Society, Vol 87, 1979.

G. J. Cox, "The impact properties of different types of ferritic spheroidal graphite cast iron," British Foundryman, 1973.

K. B. Palmer, "The mechanical and physical properties of engineering grades of cast iron at subzero temperatures," British Cast Iron Research Association, Oct, 1988.

P. J. Rickards, "The low-temperature tensile properties of nodular graphite cast irons," Cryogenics, Dec., 1969.

C. R. Wilks, N. A. Mathews, and R. W. Kraft, Jr., "Elevated Temperature Properties of Ductile Cast Irons," Transactions, American Society for Metals, 1954.

F. B. Foley, "Mechanical Properties at Elevated Temperatures of Ductile Cast Iron," Transactions, American Society for Metals, 1956.

R. O. Schelling and J. T. Eash, "Effect of Composition on the Elevated Temperature Properties of Ductile Iron," Proceedings, American Society for Testing and Materials, 1957.

K. B. Palmer, "High Temperature Properties of Cast Irons," Engineering Properties and Performance of Modern Iron Castings, British Cast Iron Research Association, Birmingham, England, 1970.

D. L. Sponseller, W. G. Scholz, and D. F. Rundle, "Low Alloy Ductile Irons for Service at 1200-1500 F," Transactions, American Foundrymen's Society, 1968.

Miller and Company, The Ductile Iron Process, 1972.

The Iron Castings Handbook, Iron Castings Society, Inc., 1981.

C. Isleib and R. Savage, "Ductile Iron-Alloyed and Normalized," Transactions, American Foundrymen's Society, Vol 65, 1957.

S. Palmer, "What is Required of Iron Castings As Engineering Components?" Engineering Properties and Performance of Modern Iron Castings, British Cast Iron Research Association, Birmingham, England, 1970.

S. I. Karsay, Ductile Iron II, Quebec Iron and Titanium Corporation, 1972.

G. N. J. Gilbert, Tensile and Fatigue Tests on Normalized Pearlitic Nodular Irons," Journal of Research, British Cast Iron Research Association, Vol 6, No 10, February 1957 pp 498-504.

K. B. Palmer and G. N. J. Gilbert, "The Fatigue Properties of Nodular Cast Iron," Journal of Research, British Cast Iron Research Association, Vol 5, No 1, August 1953, pp 2-15.

R. C. Haverstraw and J. F. Wallace, "Fatigue Properties of Ductile Iron," Gray & Ductile Iron News, Gray & Ductile Iron Founders' Society, Inc., 1966 pp 5-19.

A. G. Fuller, "Effect of Graphite Form on Fatigue Properties of Pearlitic Ductile Irons." Transactions, American Foundrymen's Society, Vol 85, 1977, pp 527-536.

M. Sofue, S. Okada and T. Sasaki, "High-Quality Ductile Cast Iron with Improved Fatigue Strength." Transactions, American Foundrymen's Society, Vol 86, 1978, pp 173-182.

K. B. Palmer, "Fatigue Properties of Cast Irons," Engineering Properties and Performance of Modern Iron Castings, British Cast Iron Research Association, Birmingham, England, 1970.

J. F. Janowak, A. Alagarsamy, and D. Venugopalan, "Fatigue Strength of Commercial Ductile Irons.", Transactions, American Foundrymen's Society, Vol 98, 1990, Paper #90-123.

Int. Komitee Giessereitechn, Vereinigungen, Fatigue Strength of Nodular Iron, VDG Technical Report No. 017, Dusseldorf, 1975.

Kolene Corporation, Detroit Michigan, Chart 6032 is Figure 3.36.

K. Roehrig, "Thermal Fatigue of Gray and Ductile Irons.", Transactions, American Foundrymen's Society, Vol 86, 1978, pp 75-88.

G. Sandoz, H. Bishop and W. Pellini, "Notch Ductility of Nodular Irons," Transactions, American Foundrymen's Society, 1954.

H. E. Mead, Jr. and W. L. Bradley, Fracture Toughness Studies of Ductile Cast Iron Using a J-Integral Approach, Transactions, American Foundrymen's Society, 1985.

K. E. Kinney, W. L. Bradley and P. C. Gerahrdt Jr., "An evaluation of the Toughness of Ductile Iron vs Cast Steel Using Modified Charpy Test Specimens." Transactions, American Foundrymen's Society, Vol 92, 1984, pp 239-250.

P. F. Timmins, "The Effect of Microstructure on Defect Tolerance in Pearlitic Spheroidal Graphite Iron." private communication, courtesy of Highland Foundry Ltd., Surrey, British Columbia, Canada.

BCIRA Broadsheet 212, "Factors influencing the ductile or brittle behaviour of nodular irons," British Cast Iron Research Association, 1982.

G. N. J. Gilbert, Engineering Data on Nodular Cast Irons, British Cast Iron Research Association, Birmingham, England, 1974.

Ductile Iron, Metals Handbook, American Society for Metals, 9th edition, Vol 15, 1988.

L. Jenkins, "Ductile Iron – an Engineering Asset.", Proceedings of the First International Conference on Austempered Ductile Iron, American Society for Metals, 1984.

R. Barton, "Embrittlement of nodular (SG) iron: its forms and prevention," Fourth International Conference of Licensees for the + GF + Converter Process, Schaffhausen, Switzerland, 1981.

G. Dinges and W. Gruver, "Temper Embrittlement of Ductile Iron," Transactions, American Foundrymen's Society, 1966.

R. A. Flinn, P. K. Trojan, and D. J. Reese, "The Behavior of Ductile Iron Under Compressive Stress," Transactions, American Foundrymen's Society, 1960.

BCIRA Broadsheet 203-5, "Density of cast iron," British Cast Iron Research Association, 1984.

Ductile Iron, International Nickel Company, New York, New York, 1956.

A. B. Everest, "Spheroidal-Graphite Cast Iron," Foundry Trade Journal, 1950, pp 57-64.

BCIRA Broadsheet 203, "Thermal conductivity of unalloyed cast irons," British Cast Iron Research Association, 1981.

L. W. L. Smith, "The determination of the thermal conductivity of cast iron," BCIRA Journal, Vol 21, 1973.

BCIRA Broadsheet 203-3, "Electrical resistivity of unalloyed cast iron," British Cast Iron Research Association, 1984.

K. B. Palmer, "The electrical resistivity of cast iron," BCIRA Journal, June, 1953.

M. Decrop, "Le Magnetisme des Fontes," Fonderie, July, 1963.

BCIRA Broadsheet 203-7, "Specific heat capacity of cast irons," British Cast Iron Research Association, 1985.

H. T. Angus, Cast Iron: Physical and Engineering Properties, 2nd ed., Butterworths Inc, 1967.

C. F. Walton, Gray Iron castings Handbook, Gray and Ductile Iron Founders' Society, Cleveland, Ohio, 1958.

BCIRA Broadsheet 203-5, "Density of cast irons," British Cast Iron Research Association, 1984.

G. N. J. Gilbert and C. L. Pidgeon, "The growth and scaling properties of cast irons in air at temperatures of 350 °C and 400 °C for times up to 21 years," BCIRA Journal, July, 1982.

SECTION III

E. Plenard, ''Cast Iron Damping Capacity, Structure and Related Properties,'' Transactions, American Foundrymen's Society, Vol 70, 1962, pp 298-305.

E. Plenard, Damping Capacity of Cast Iron, Foundry Trade Journal, Oct, 1966, pp 541-549.

Annual Book of ASTM Standards, Volume 01.02, Ferrous Castings, 1987.

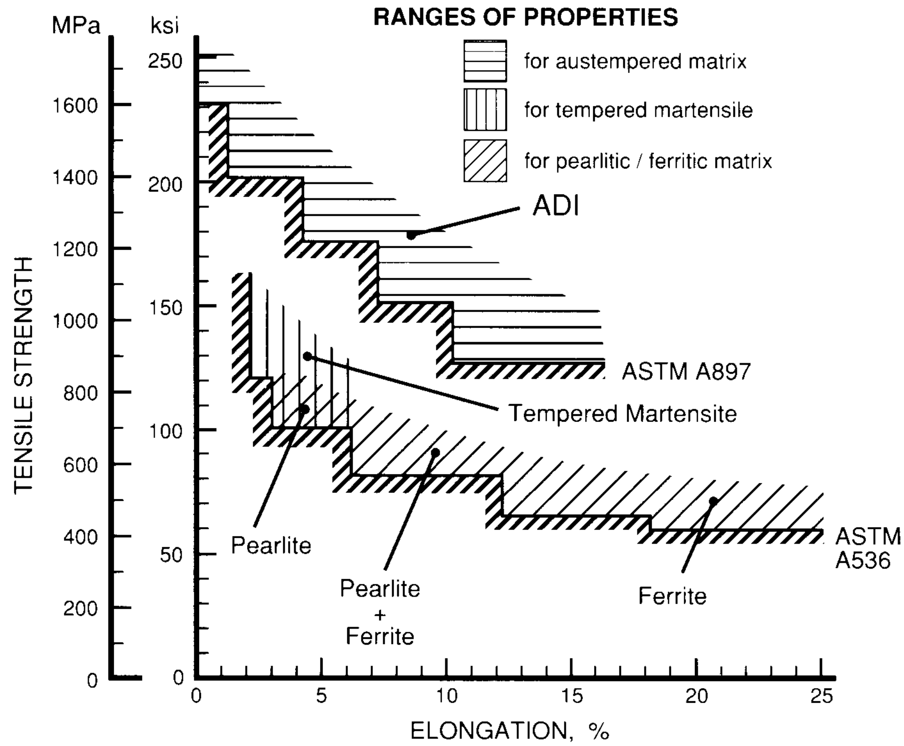
Cast Metals Handbook, American Foundrymen's Society, 1957.

Back to Table of Contents

SECTION IV

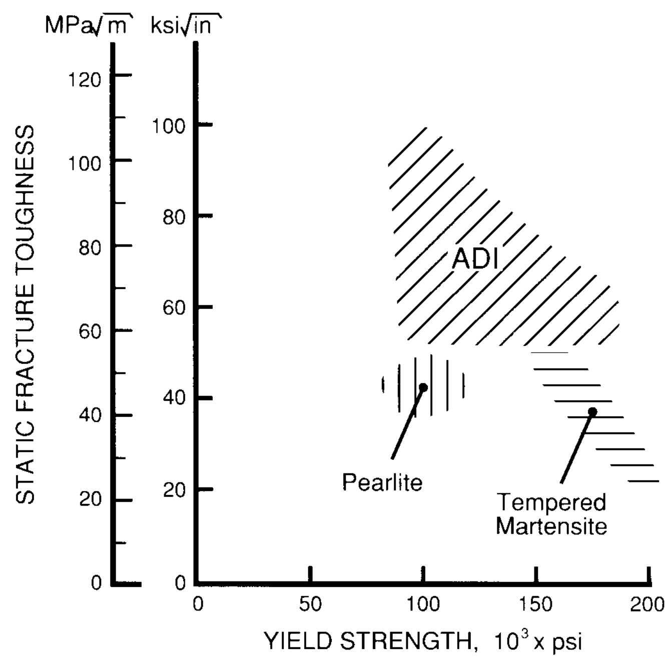
AUSTEMPERED DUCTILE IRON

Figure 4.1



Tensile properties of ADI and conventional Ductile Iron.

Figure 4.2



Fracture toughness of ADI and conventional Ductile Iron.

AUSTEMPERED DUCTILE IRON

Introduction

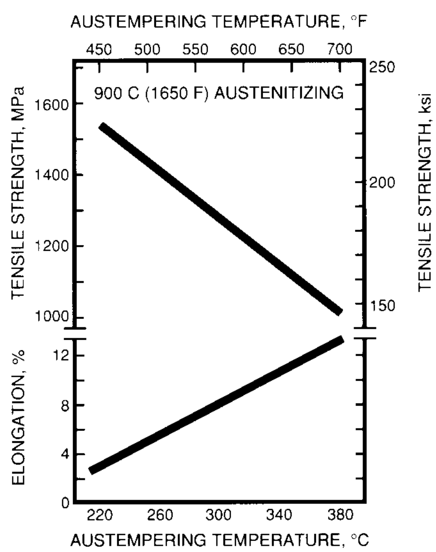
What material offers the design engineer the best combination of low cost, design flexibility, good machinability, high strength-to-weight ratio and good toughness, wear resistance and fatigue strength? Austempered Ductile Iron (ADI) may be the answer to that question. ADI offers this superior combination of properties because it can be cast like any other member of the Ductile Iron family, thus offering all the production advantages of a conventional Ductile Iron casting. Subsequently it is subjected to the austempering process to produce mechanical properties that are superior to conventional Ductile Iron, cast and forged aluminum and many cast and forged steels.

Figures 4.1 and 4.2 compare the mechanical properties of ADI to those of conventional Ductile Irons. Figure 4.1 also provides a comparison between the tensile strength-elongation relationships for the ASTM A897 ADI specification and that of the ASTM A536 specification for conventional Ductile Iron. These, and other Ductile Iron specifications are discussed in further detail in Section XII. Compared to the conventional grades of Ductile Iron, ADI delivers twice the strength for a given level of elongation. In addition, ADI offers exceptional wear resistance and fatigue strength.

Figure 4.3a shows the strength of Ductile Iron and ADI compared to cast and forged steels. Ductile Iron has commercially replaced as cast and forged steels in the lower strength region, now ADI is finding

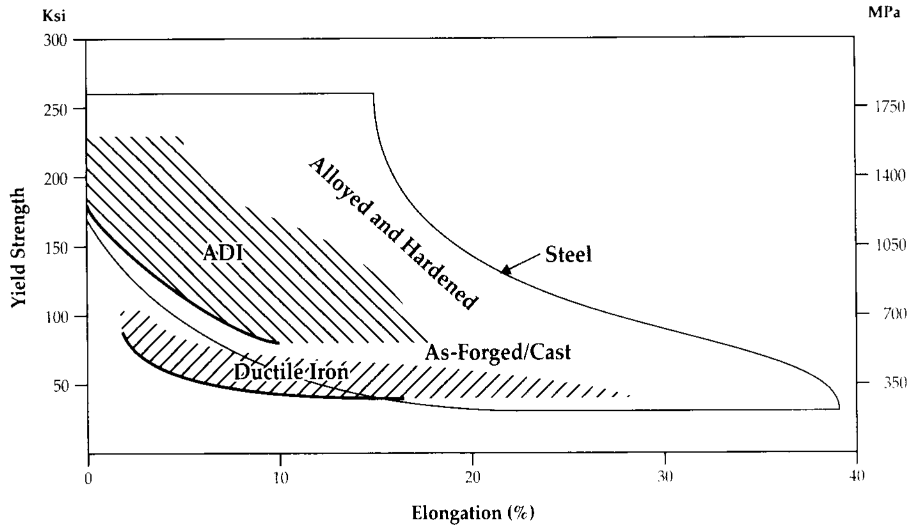
SECTION IV

Figure 4.3



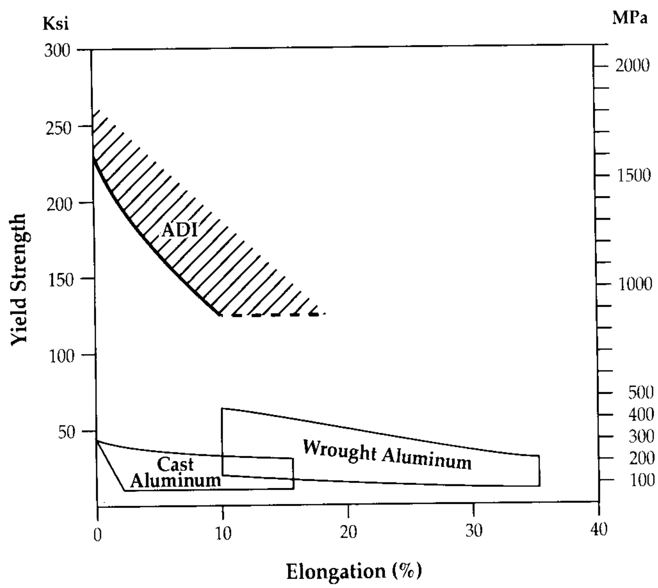
Effect of austempering temperature on the tensile properties of ADI.

Figure 4.3a



Comparative strength of steel vs. Ductile Iron.

Figure 4.3b

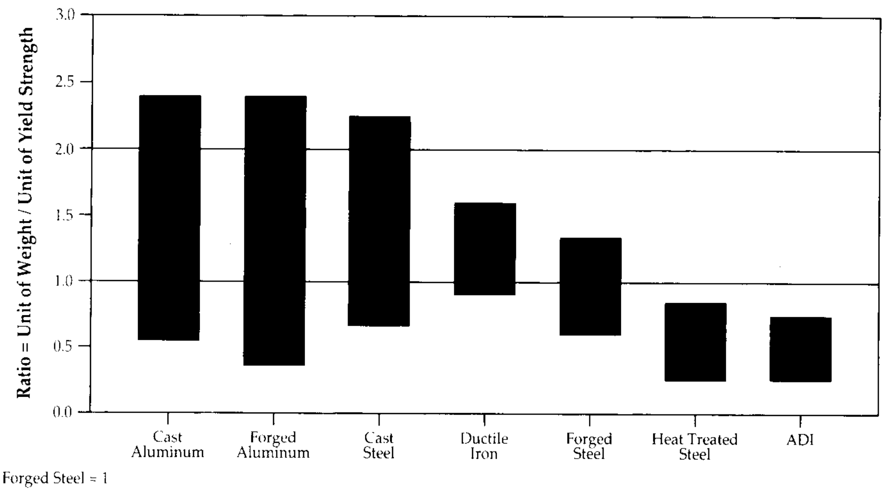


ADI vs. Aluminum.

applications in the higher strength regions. As shown in Figure 4.3b, the yield strength of ADI is over three times that of the best cast or forged aluminum. In addition ADI weighs only 2.4 times more than aluminum and is 2.3 times stiffer. ADI is also 10% less dense than steel. Therefore, when you compare the relative weight per unit of yield strength of ADI with that of various aluminums and steels (Figure 4.4) it is easy to see the engineering and design advantages inherent in ADI.

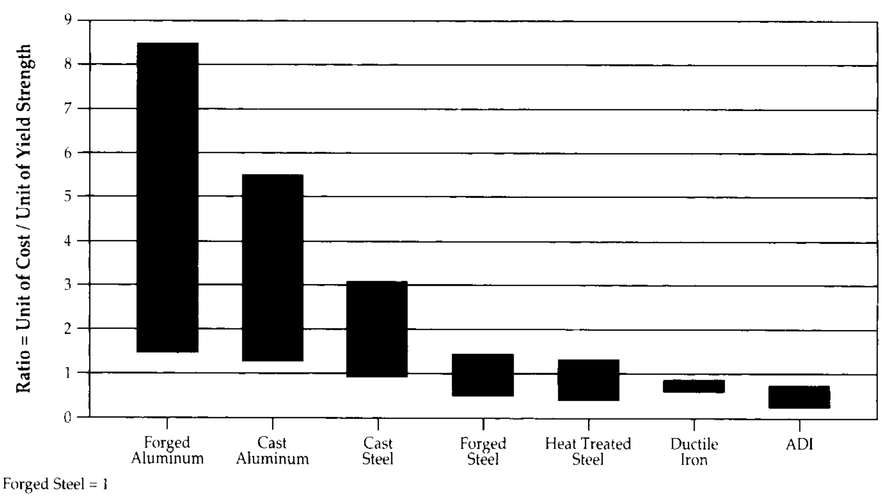
For a typical component, ADI costs 20% less per unit weight than steel and half that of aluminum. When we now analyze the cost-per-unit-strength of ADI vs. various materials (Figure 4.5) the economic advantages of ADI become apparent.

Figure 4.4



Relative weight per unit of yield strength.

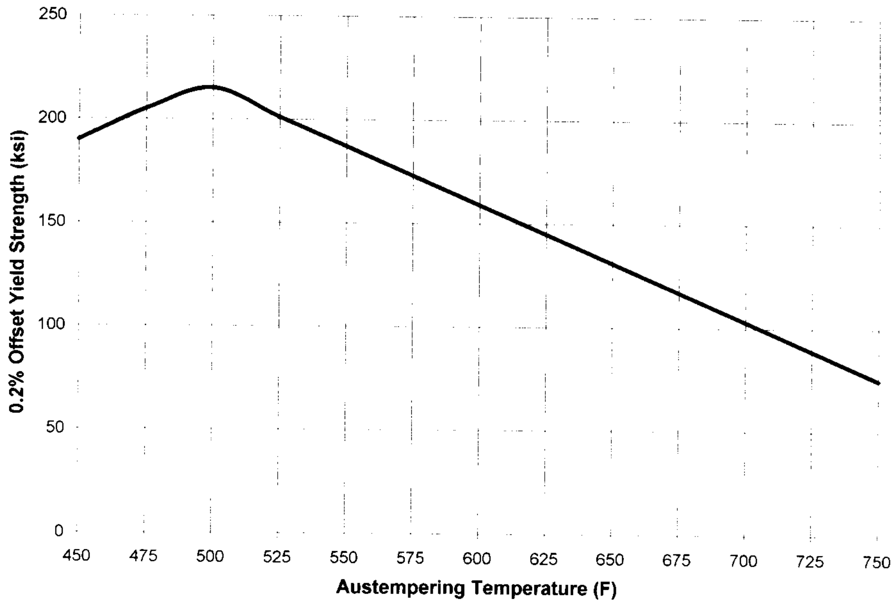
Figure 4.5



Relative cost per unit of yield strength.

SECTION IV

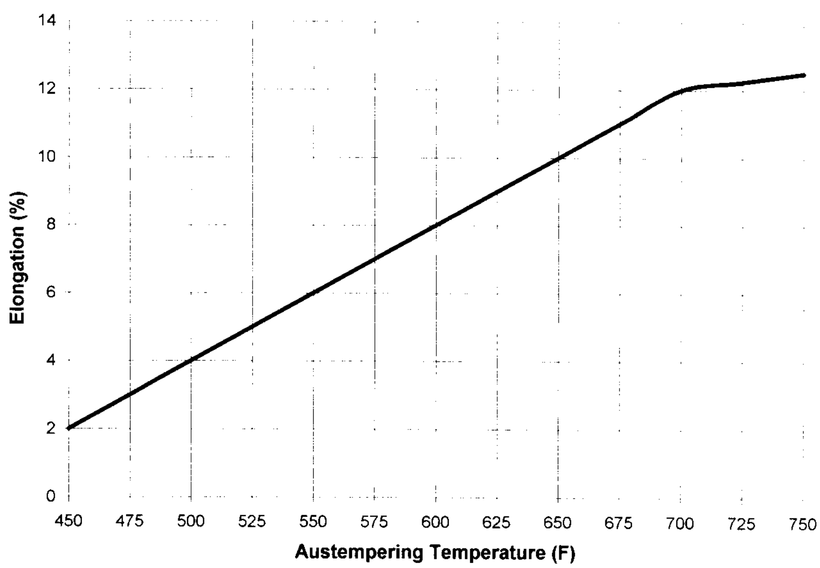
Figure 4.6a



Typical ADI yield strength vs austempering temperature.

SECTION IV

Figure 4.6b



Typical ADI elongation vs austempering temperature.

The mechanical properties of Ductile Iron and ADI are primarily determined by the metal matrix. The matrix in conventional Ductile Iron is a controlled mixture of pearlite and ferrite. (Tempered martensitic matrices may be developed for wear resistance, but lack the ductility of either as-cast Ductile Iron or ADI). The properties of ADI are due to its unique matrix of acicular ferrite and carbon stabilized austenite; called Ausferrite. The austempering process is neither new or novel and has been utilized since the 1930's on cast and wrought steels. The austempering process was first commercially applied to Ductile Iron in 1972 and by 1998 worldwide production was approaching 100,000 tonnes annually.

The preponderance of information on the austempering of steel and the superficial similarities between the austempering heat treatments applied to steels and ADI, have resulted in comparisons which are incorrect and damaging to the understanding of the structure and properties of ADI. ADI is sometimes referred to as "bainitic Ductile Iron", but correctly heat treated ADI contains little or no bainite. Bainite is a matrix of acicular (plate-like) ferrite and carbide. ADI's ausferrite matrix is a mix of acicular ferrite and carbon stabilized austenite. This ausferrite may resemble bainite metallographically, however it is not because it contains few or none of the fine carbides characteristic in bainite. An ausferrite matrix will only convert to bainite if it is over tempered.

The presence of austenite in ADI also leads to a harmful misconception. It is "retained" in the sense that it has persisted from the austenitizing treatment, but it is not the "retained austenite" that designers and metallurgists equate with unstable, incorrectly heat treated steel. The austenite in ADI has been stabilized with carbon during heat treatment and will not transform to brittle martensite even at sub-zero temperatures.

The presence of stable, carbon enriched austenite also accounts for another inadequately understood property of ADI. While thermodynamically stable, the enriched austenite can undergo a strain-induced transformation when exposed to high, normal forces. This transformation, which gives ADI its remarkable wear resistance, is more than mere "work hardening". In addition to a significant increase in flow stress and hardness (typical in most metallic materials), this strain induced transformation also produces a localized increase in volume and creates high compressive stresses in the "transformed" areas. These compressive stresses inhibit crack formation and growth and produce significant improvements in the fatigue properties of ADI when it is machined after heat treatment or subjected to surface treatments such as shot peening, grinding or rolling. (See Section IX).

Mechanical Properties

ADI is a group of materials whose mechanical properties can be varied over a wide range by a suitable choice of heat treatment. Figure 4.6 illustrates the strong correlation between austempering temperature and tensile properties. A high austempering temperature, 750°F (400°C),

Figure 4.7 **Statistical evaluation of the tensile properties of Grade 125/80/10 ADI versus ASTM requirements.**

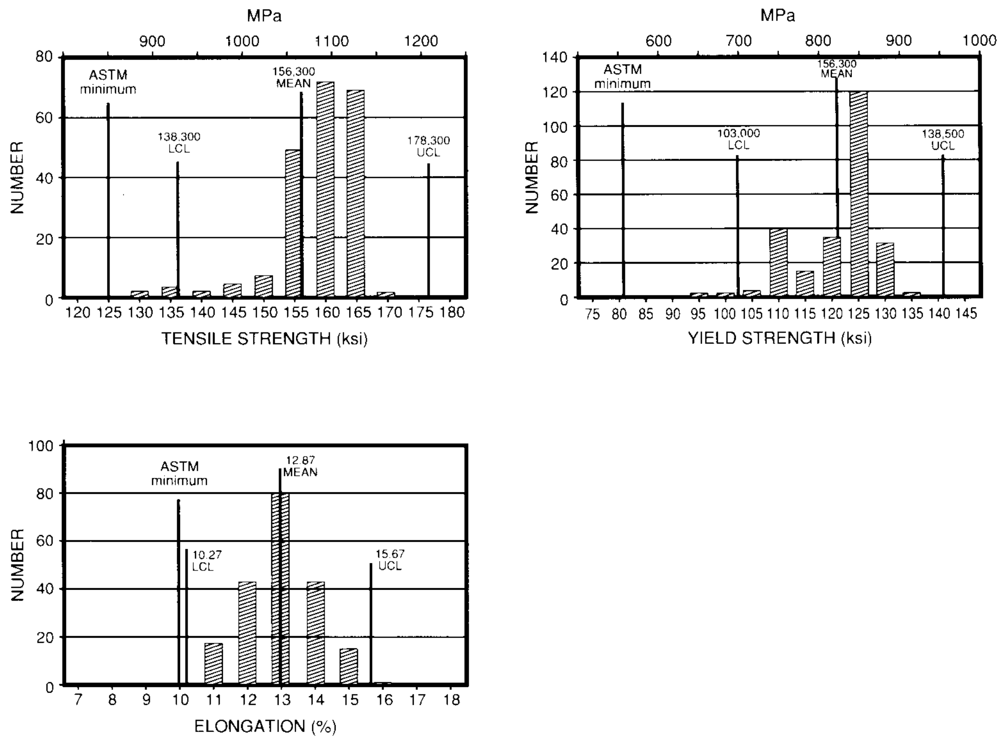
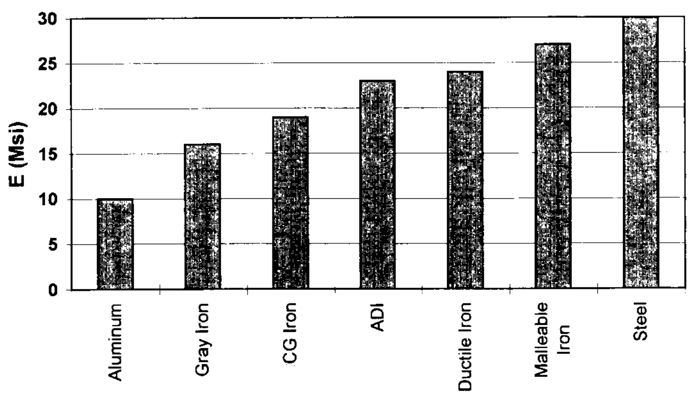


Figure 4.8



Typical young's modulus for various materials.

produces ADI with high ductility, a yield strength in the range of 500 MPa (72 ksi) with good fatigue and impact strength. These grades of ADI also respond well to the surface strain transformation previously discussed which greatly increases their bending fatigue strength. A lower transformation temperature, 500°F (260°C), results in ADI with very high yield strength (1400 MPa (200 ksi)), high hardness, excellent wear resistance and contact fatigue strength. This high strength ADI has lower fatigue strength as-austempered but it can be greatly improved with the proper rolling or grinding regimen. Thus, through relatively simple control of the austempering conditions ADI can be given a range of properties unequaled by any other material.

Tensile Properties

Like other Ductile Iron specifications presented in Chapter XII, ASTM A897 defines the minimum tensile properties for different grades of ADI. Figure 4.1 indicates that the ranges of properties exhibited by ADI exceed these minima, but does not offer quantitative evidence on which materials selection decisions can be made with confidence. Competent producers of both conventional Ductile Iron and ADI recognize that they must not only provide statistically significant mechanical property data, but also give evidence of SPC and their commitment to continual improvement. Figure 4.7 provided by CMI International offers statistical evidence that grade 125/80/10 ADI can be produced with mechanical properties significantly in excess of those required by the specification. (The data shown represent 18 months of foundry production and over 600 heat treat lots).

The modulus of elasticity in tension for ADI lies in the range of 22.5-23.6 X 10^6 psi (155-163 GPa). Figure 4.8 shows the relationship of ADI's Young's Modulus to that of other materials.

Fracture Toughness

Traditionally, components have been designed on the basis of preventing failure by plastic deformation. As a result, design codes used either the 0.2% yield stress or the ultimate tensile stress when specifying material properties, and designers then applied a safety factor when determining the acceptable working stress level in the component. Both designers and metal casters have recognized that structures also fail by brittle fracture and fatigue, especially in the presence of a crack-like defect. As a result, fracture toughness, the intrinsic resistance of the material to crack propagation, is becoming an essential part of the package of material properties used by designers to select materials for critical applications.

There is a dearth of fracture toughness data for ADI, for two very valid reasons. First, being a relatively new material, efforts to define a mechanical property database have concentrated on the more conventional and

Table 4.1

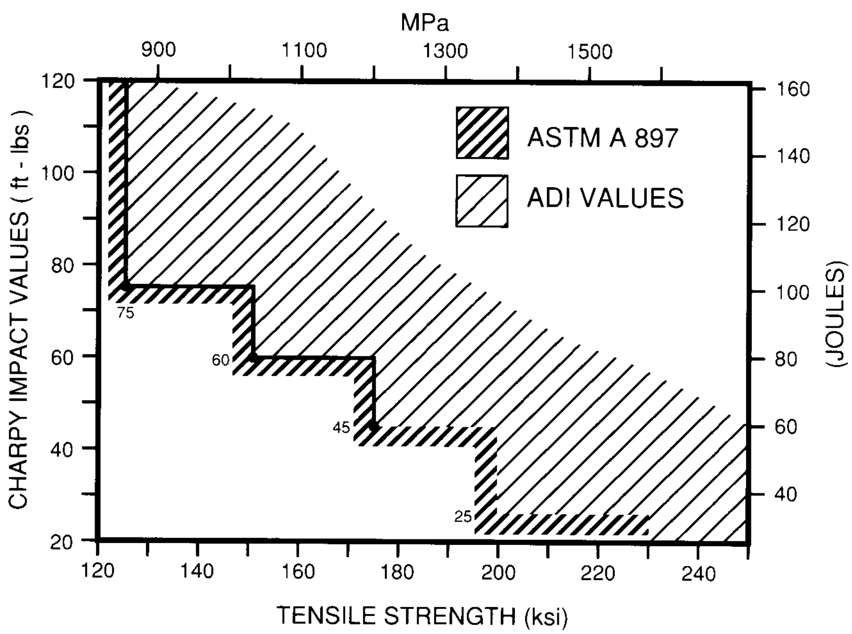
Comparison of the mechanical properties of forged steel, pearlitic Ductile Iron and Grade 150/100/7 ADI.

Mechanical Property	MATERIAL Forged steel	Pearlitic Ductile Iron	Grade 150/100/7 ADI
Yield strength, ksi (mPa)	75 (520)	70 (480)	120 (830)
Tensile strength, ksi (mPa)	115 (790)	100 (690)	160 (1100)
Elongation, %	10	3	10
Hardness, Bhn	262	262	286
Impact strength**, ft-lb (joules)	130 (175)	40 (55)	120 (165)

** Un-notched charpy at room temperature.

SECTION IV

Figure 4.9



Charpy impact values for ADI versus ASTM requirements.

easily acquired tensile properties, with early efforts at defining toughness being confined largely to an extension of the notched and un-notched Charpy test used to characterize conventional Ductile Irons. Second, the more ductile grades of ADI, for which fracture toughness is a critical property, do not behave in a linear elastic manner when subjected to standard LEFM tests, and toughness must be determined by yielding fracture mechanics techniques such as the J integral crack opening displacement (COD) tests. Nevertheless, when the combined knowledge of the toughness properties is assembled, they reveal three important facts:

1. Considering its high strength, ADI has very good toughness,

2. Where valid comparisons exist, the toughness of ADI is much greater than that of conventional Ductile Iron and equivalent or superior to competitive cast and forged steels, and

3. Like other properties of ADI, its toughness is strongly dependent on microstructure (and thus, the grade of ADI).

Figure 4.2 shows that ADI heat treated to produce high strength has a static fracture toughness of 55-70 $MPa(m)^{1/2}$, which is greater than that of Ductile Iron with a matrix of tempered martensite or pearlite. Furthermore, it shows that ADI heat treated to a lower strength (higher ductility) grade has a fracture toughness in excess of 100 $MPa(m)^{1/2}$, twice as tough as pearlitic Ductile Iron. When compared to forged steel and conventional Ductile Iron, both with equal or inferior mechanical properties, ADI exhibits un-notched Charpy impact values at room temperature that are less than those of forged steel, but three times higher than conventional Ductile Iron (Table 4.1). Figure 4.9 shows that the room temperature un-notched Charpy values of ADI are substantially higher than those required by ASTM A897-90 at all levels of strength.

Table 4.2 provides a comparison of yield strength and fracture toughness, K_{1C}, between ADI, conventional austenitic Ductile Irons, and quenched and tempered AISI 4140 and 4340 steels. With K_{1C}, values in the range of 59-86 $MPa(m)^{1/2}$, ADI had a fracture toughness which was superior to all other Ductile Irons, except Ni-Resist, and equal to or higher than most of the quenched and tempered steels. This table also compares the ratio of K_{1C} to yield strengh for these materials. This ratio, which is proportional to the size of flaw that can be tolerated when materials are stressed to a constant fraction of their yield strength, indicates that ADI has equal or greater flaw tolerance than pearlitic Ductile Iron and quenched and tempered steels.

Table 4.2 **Comparison of yield strength, fracture toughness and flaw tolerance between ADI, conventional and austenitic Ductile Irons, and quenched and tempered steels.**

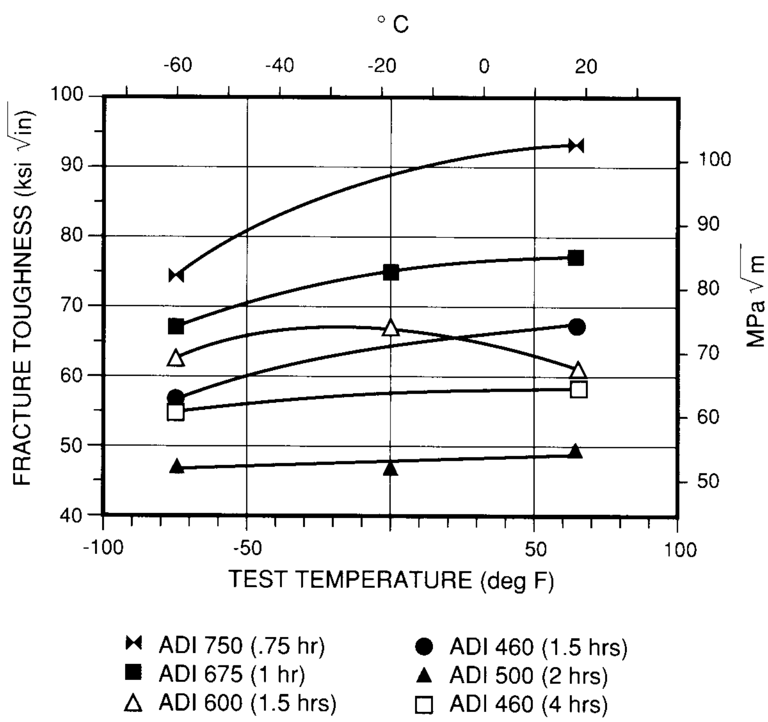
Alloy	Heat Treatment	σ_y (MPa)	K_{IC} (MPa-m$^{1/2}$)	$\left(\frac{K_{IC}}{\sigma_y}\right)^2$ (mm)
A—2	850°C, 1 hr —salt quench→ 260°C*	1205.4	73.49	3.72
	" 300°C	1107.4	68.62	3.84
	" 350°C	989.8	72.10	5.30
	" 400°C	744.8	72.91	9.58
	" 430°C	744.6	74.52	10.00
B—5	850°C, 1 hr → 260°C	1029.0	75.18	5.34
	" 300°C	980.1	75.40	5.92
	" 350°C	793.7	73.68	8.62
	" 400°C	756.0	76.01	10.08
C—1	850°C, 1 hr → 300°C	1151.5	86.00	5.58
C—3	850°C, 1 hr → 300°C	1199.5	78.20	4.25
	" 350°C	900.3	61.60	4.68
	" 400°C	908.8	59.40	4.27
C—5	850°C, 1 hr → 300°C	1118.2	85.74	5.88
Ductile Iron, Ferritic, 1.55% Si, 1.5% Ni, 1.2% Ni		269	42.8	25.3
Ductile Iron, Ferritic, 3.6% C, 2.5% Si, 0.38% Ni, 0.35% Mo		331	48.3	21.3
Ductile Iron, Pearlitic, 0.5% Mo		483	48.3	10.0
Ductile Iron, 80—60—03		432	27.1	3.9
Ductile Iron, D7003		717	51.7	5.2
Ductile Iron, Ni—Resist D-5B		324	64.1	39.1
(Above Data from: Iron Castings Handbook, 1981, p.357)				
AISI 4140**	870°C, 1 hr, Oil Quench → 204°C	1449	43.80	0.92
	280°C	1587	55.00	1.20
	396°C	1518	55.60	1.34
	1100°C, 1 hr, Oil Quench → 204°C	1380	65.05	2.22
	246°C	1449	57.25	1.56
	1200°C, 1 hr, Oil Quench → 204°C	1380	89.12	4.18
	246°C	1449	72.64	2.52
	323°C	1414.5	53.30	1.42
	348°C	1393.8	58.46	1.76
AISI 4340**	870°C, 1 hr, Oil Quench → 200°C	1345	65.38	2.36
	280°C	1504.2	66.81	1.97
	350°C	1497.3	87.69	3.43
	400°C	1449.0	100.22	4.78
	1200°C, 1 hr, Oil Quench → 246°C	1380.0	90.55	4.31
	280°C	1393.8	69.01	2.45
	843°C, OQ, Tempered 260°C	1642.2	48.79	0.88
	427°C	1421.4	84.47	3.53

* Isothermal Transformation Time: 1 Hour.

** Data obtained from: Damage Tolerance Design Handbook, Metals and Ceramics Information, Battle Columbus Laboratories, January 1975.

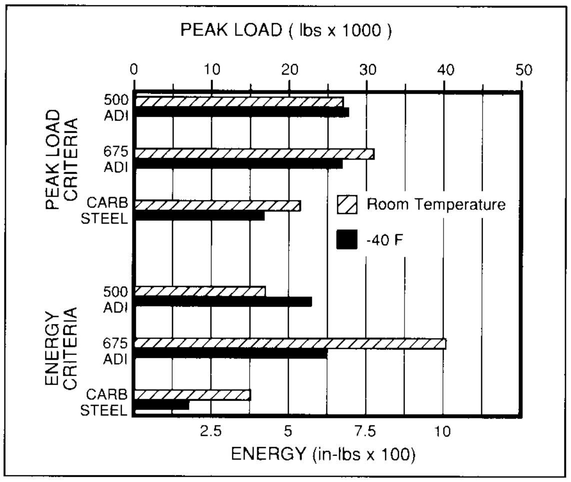
The ASME Gear Research Institute used both the ASTM Short Rod Fracture Test (SRFT) and the non-standard Single Tooth Impact (STI) test to evaluate various ADI materials for gear applications and compare their fracture toughness with carburized 8620 steel. Figure 4.10 shows ASTM Short Rod Fracture Toughness for ADI ranging from 55 to 105 $MPa(m)^{1/2}$ at room temperature. This compares favorably with a reported room temperature fracture toughness of 22 to 33 $MPa(m)^{1/2}$ for carburized and hardened 8620 steel. The ADI toughness levels increase strongly with increasing austempering temperature. (The austempering condition is indicated in degrees F and hours; i.e. ADI 750(.75 hr) was austempered at 750°F for 45 minutes).

Figure 4.10



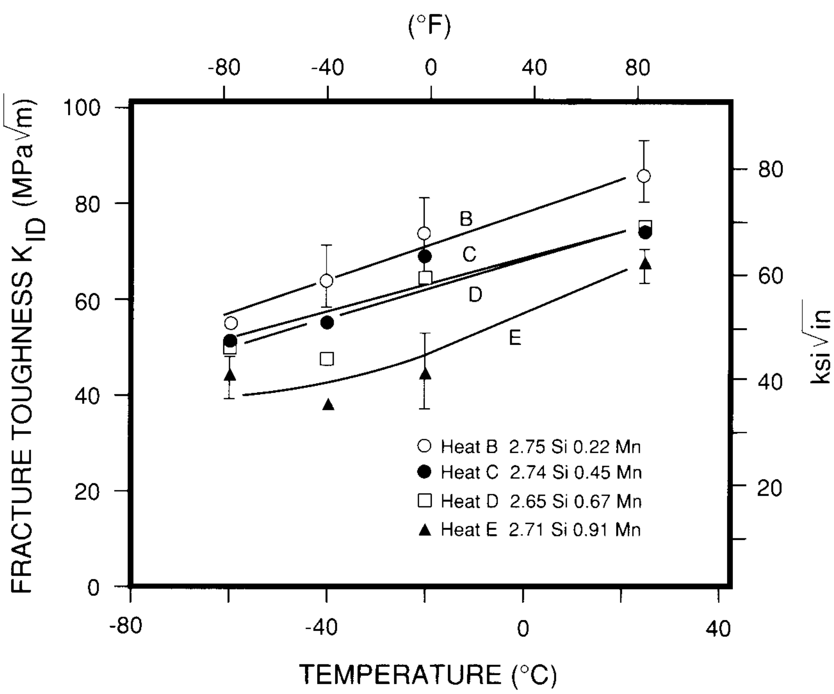
Effect of heat treatment and test temperature on ASTM SRFT toughness values of ADI.

Figure 4.11



Single tooth impact toughness data for ADI and carburized gear steel.

Figure 4.12



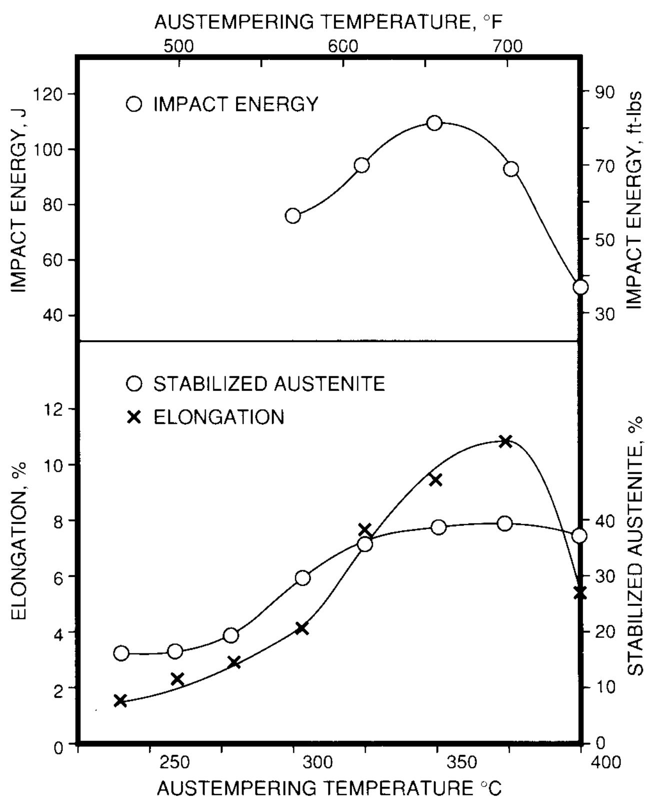
Effect of manganese content on dynamic fracture toughness properties of ADI.

The Single Tooth Impact test results shown in Figure 4.11 are consistent with Short Rod Fracture Toughness data, with ADI superior to carburized steel for both peak load and fracture energy criteria at both room temperature and -40 degrees.

Figure 4.12 illustrates ADI dynamic fracture toughness data which were produced by instrumented impact tests performed on Charpy-size specimens. The results, in the range of 40 to 80 $MPa(m)^{1/2}$, show that toughness decreases with higher levels of manganese.

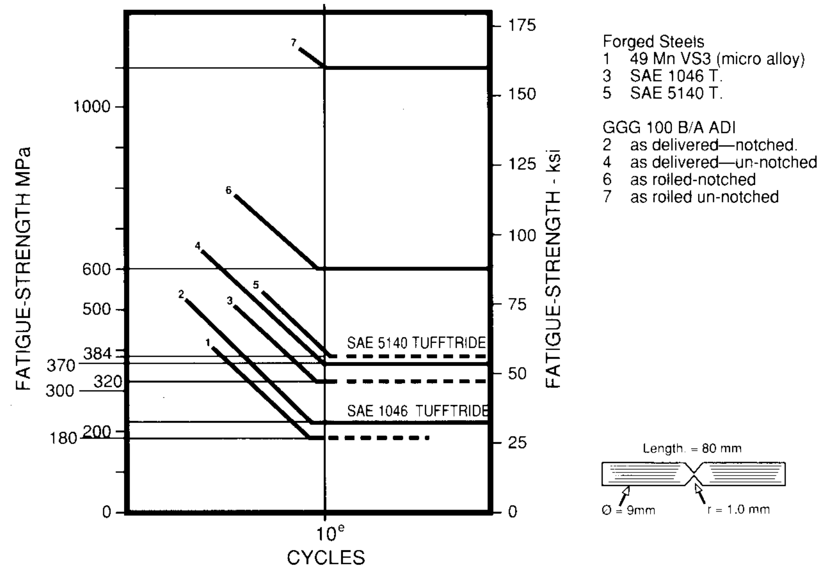
Regardless of the type of toughness test, ADI results were superior to those of conventional Ductile Iron, and were equal to, or better than competitive steels. Additionally, all toughness tests revealed that the toughness of ADI increases with austempering temperature to a maximum around 650-700°F (340-370°C). Figure 4.13 confirms that this relationship is a further manifestation of the influence of the volume fraction of stabilized austenite on the ductility and toughness of ADI.

Figure 4.13



Relationships between impact energy, elongation, stabilized austenite and austempering temperature.

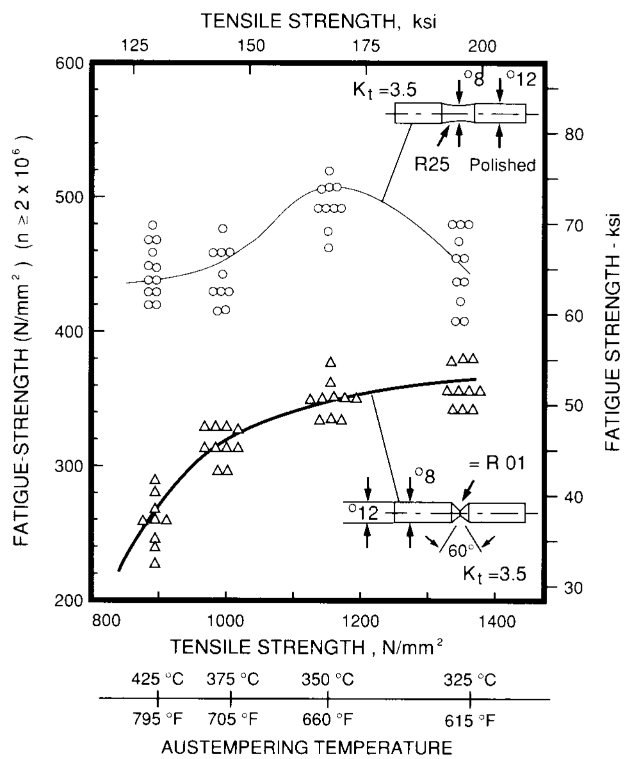
Figure 4.14



Comparison of fatigue properties of ADI and different grades of forged steel.

SECTION IV

Figure 4.15



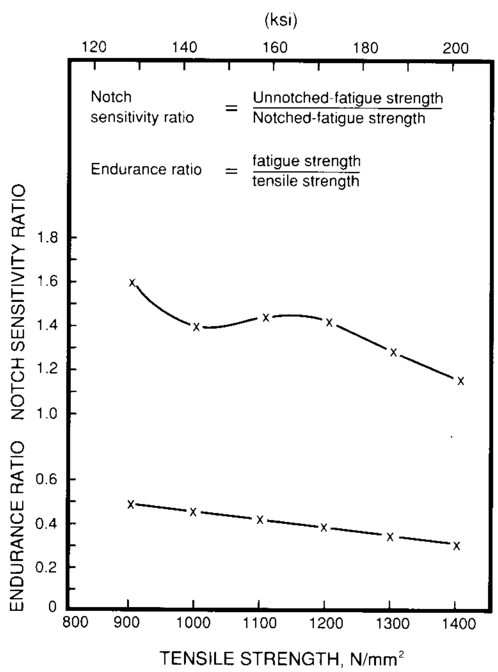
Fatigue properties of notched and un-notched ADI.

An extensive work done at National University of Mar del Plata (Argentina) compared the properties of ADI to those of 4140 steel. It concluded that while a standard notched Charpy test indicated that the properties of ADI were inferior to those of 4140 steel, fracture toughness tests indicate "a much less significant difference". In fact, it was found that the strain rate of the fracture test had a much more significant effect on the steel than on the ADI. It concluded that "the comparison of toughness of ADI and steels, should not be based on the impact energy measurements. Fracture mechanics properties, such as K_{1C}, should be used for design purposes".

Fatigue

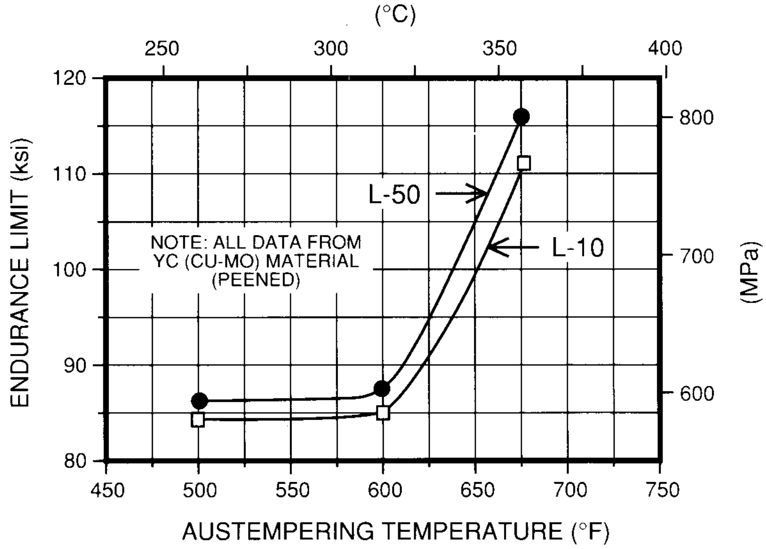
As shown in Figure 4.14, ADI has fatigue properties equal or superior to those of forged steels. When subjected to surface treatments such as rolling, peening or machining after heat treatment, the fatigue strength of ADI is increased significantly. (See Figures 3.34, 3.35 and Table 3.3 in Section III, and Figures 4.35 and 4.36. Figures 4.14 and 4.15 also indicate that ADI is moderately notch sensitive in fatigue, with a notch sensitivity ratio (ratio of notched to un-notched endurance limits) ranging from 1.2 to 1.6 (see Figure 4.16) for the notch geometry tested. Conventional ferritic and pearlitic Ductile Irons have a notch sensitivity of about 1.6 and steels fatigue strengths similar to ADI exhibit notch sensitivity ratios as high as 2.2-2.4. To avoid problems caused by notch sensitivity, components with sharp corners should be redesigned to provide generous fillets and radii. When required, fillet rolling or shot peening can be employed to further increase resistance to fatigue failure.

Figure 4.16



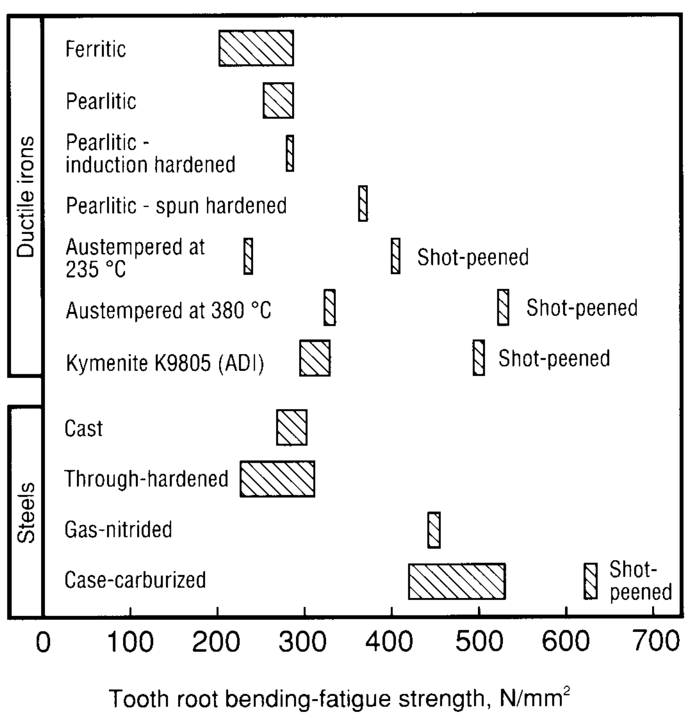
Relationships between the tensile strength of ADI and its endurance ratio and notch sensitivity ratio.

Figure 4.17



Relationship between fatigue endurance limit of peened ADI and austempering temperature.

Figure 4.18



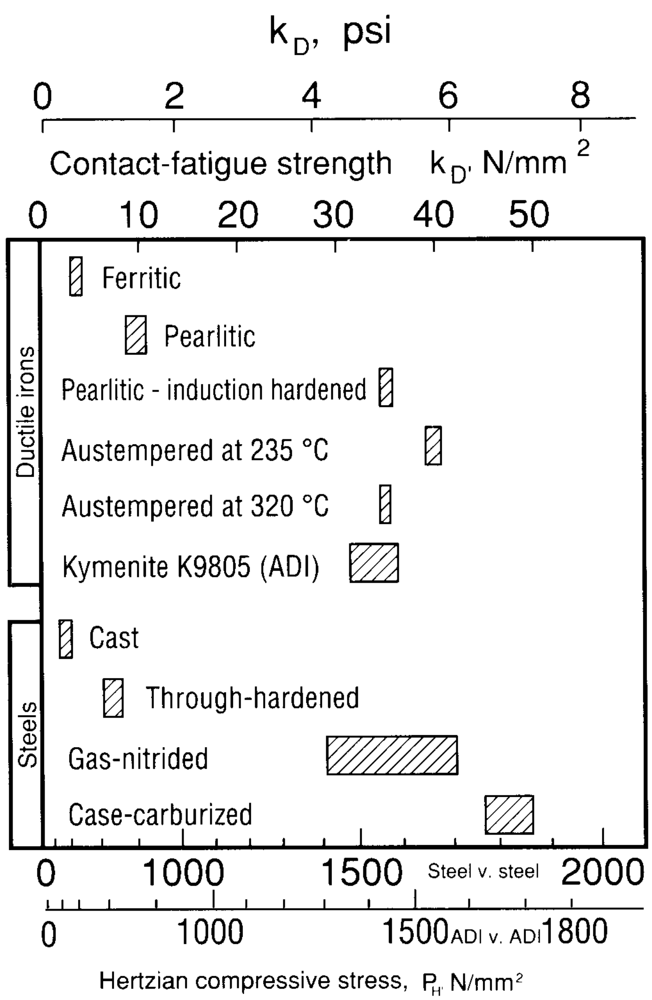
Comparison of bending-fatigue strength of ADI with those of conventional Ductile Iron and steels used for gear applications.

SECTION IV

Figure 4.15 relates the fatigue strengths fo notched and un-notched ADI to tensile strength and austempering temperature. Comparison of this figure with Figure 4.13 reveals several interesting facts. Unlike conventional Ductile Iron, the un-notched fatigue limit of ADI does not follow the tensile properties, demonstrates a maxima at the condition of lower tensile strength and maximum stabilized austenite content in the metal matrix. These relationships result in an endurance ratio (ratio of fatigue strength to tensile strength) that is 0.5 for lower strength ADI and decreases to 0.3 as the tensile strength increases to its maximum. (See Figure 4.16). The notched ADI fatigue strengths shown in Figure 4.15 increase rapidly with tensile strength and, as a result, high strength ADI is the least notch sensitive.

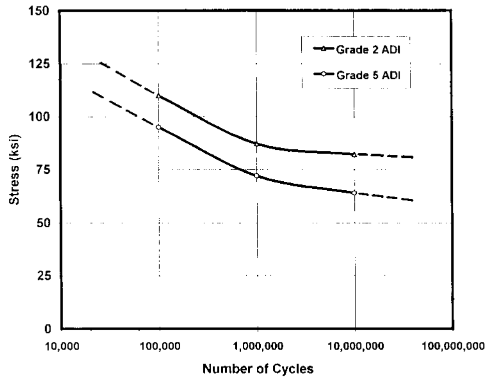
Figure 4.17 shows an important relationship between austempering temperature and the endurance limit of shot peened ADI. The dramatic

Figure 4.19



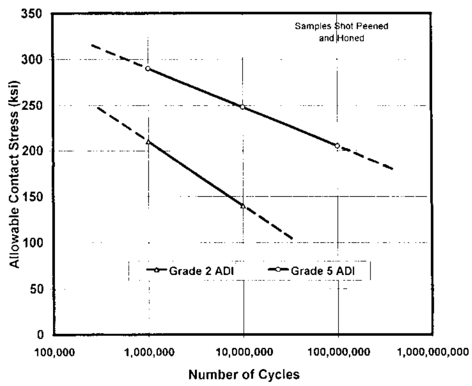
Comparison of contact fatigue strengths of ADI with those of conventional Ductile Iron and steels used for gear applications.

Figure 4.20



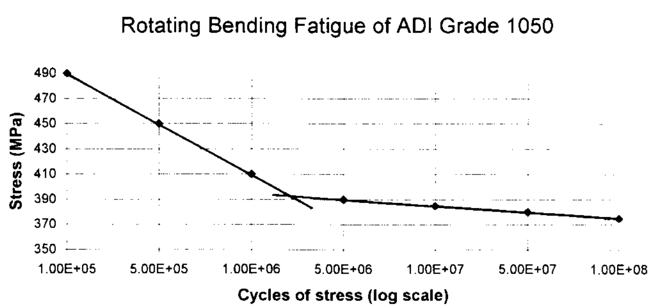
**Single tooth bending fatigue (90% confidence limits).
(From ASME Gear Research Institute)**

Figure 4.21



**Contact fatigue (90% confidence limits).
(From ASME Gear Research Institute)**

Figure 4.22



Typical fatigue curve denoting high load/low cycle region and low load/high cycle region.

Table 4.3

Typical fatigue coefficients and exponents for 300 BHN ADI

Strength Coefficient K (ksi / MPa)	218 / 1503
Strain Hardening Exponent n	0.143
True Fracture Strength s_f	150 / 1032
True Fracture Ductility e_f	0.082
Strength Coefficient K' (ksi / MPa)	253 / 1744
Strain Hardening Exponent n'	0.1330
Fatigue Strength Coefficient s_f' (ksi / MPa)	211 / 1455
Fatigue Strength Exponent b	-0.0900
Fatigue Ductility Coefficient e_f'	0.1150
Fatigue Ductility Exponent C	-0.5940

rise in endurance limit in ADIs austempered above 600°F (315°C) is related to the increased response to peening resulting from the higher austenite contents characteristic of higher austempering temperatures.

Figures 4.18 and 4.19 indicate that for gear applications, shot peened ADI has single tooth bending fatigue and contact fatigue superior to as cast and conventionally heat treated Ductile Irons, and cast and through hardened steels. They also show that peened ADI is competitive with gas nitrided and case carburized steels.

To this point we have discussed fatigue strength in terms that assume infinite life below a certain load. In fact, as the number of loading cycles are increased all materials undergo changes in their ability to withstand further loading. Figure 20 shows the relationship between number of cycles and the allowable **single tooth bending** stress (in ksi). Grade 2 ADI represents an ADI austempered at 675°F (357°C) and Grade 5 represents an ADI austempered at 500°F (260°C). Figure 21 shows the relationship between the number of cycles and the **allowable contact stress** for those same ADIs. Figure 22 shows the relationship of number of cycles to allowable **rotating bending stress** for a Grade 1050 ADI (austempered at 675°F (357°C)) in the as-austempered condition.

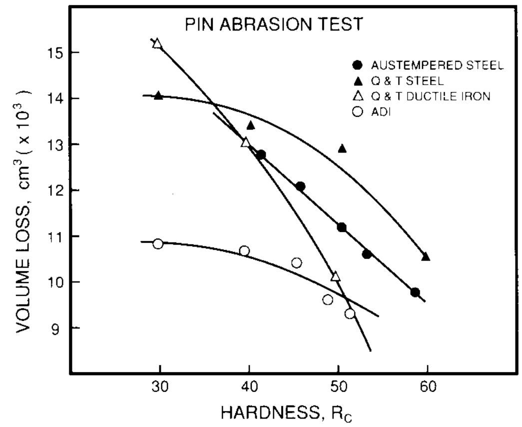
To accurately model the finite element behavior of materials that are dynamically loaded the design engineer uses certain coefficients and exponents to predict a component's fatigue behavior. As of this writing much work is being done to develop those numbers for Ductile Irons and ADI. Table 4.3 shows the typical fatigue coefficients and exponents for a 300 BHN ADI. (Courtesy of Ford Motor Company and Meritor Heavy Vehicle Systems).

Abrasion Resistance

Austempered Ductile Iron offers the design engineer abrasion resistance that is superior to competitive materials over a wide range of hardness. Generally, ADI will outwear competitive materials at a given hardness level. For example (from Figure 4.23) an ADI component at 30 to 40 Rc will wear comparably to a quenched and tempered steel component at nearly 60 Rc in an abrasive wear environment. This property, shown in Figures 4.23 and 4.24, allows the designer to select the combination of strength, ductility and abrasion resistance that will provide the best component performance in a particular application.

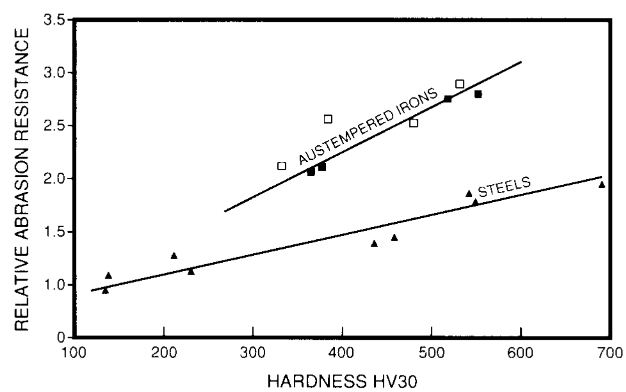
The superior abrasion resistance, and the low sensitivity of abrasion resistance to bulk hardness are related to the strain-induced transformation of stabilized austenite which occurs when the surface of an ADI component is subjected to deformation. The result of this transformation is a significant increase in surface hardness shown in Figure 4.25. This increase in surface hardness, and its relationship to microstructure, are responsible for the reduced sensitivity of abrasion resistance to hardness. As the bulk hardness of ADI i reduced by the austempering temperature, the amount of stabilized austenite increases (see

Figure 4.23



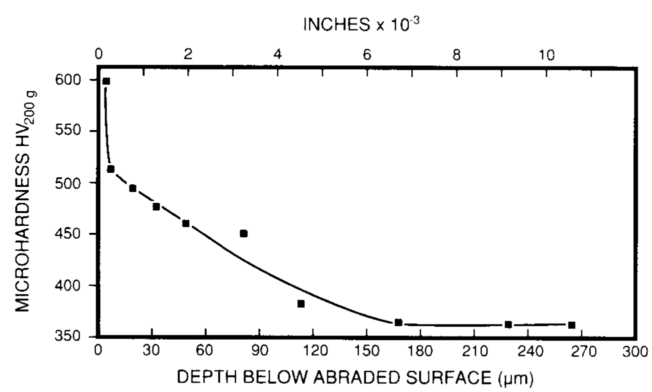
Comparison of pin abrasion test results of ADI, Ductile Iron and two abrasion resistant steels.

Figure 4.24



Comparison of the relative abrasion resistance (RAR) of ADI with those of different abrasion resistant steels. High RAR values indicate higher abrasion resistance.

Figure 4.25

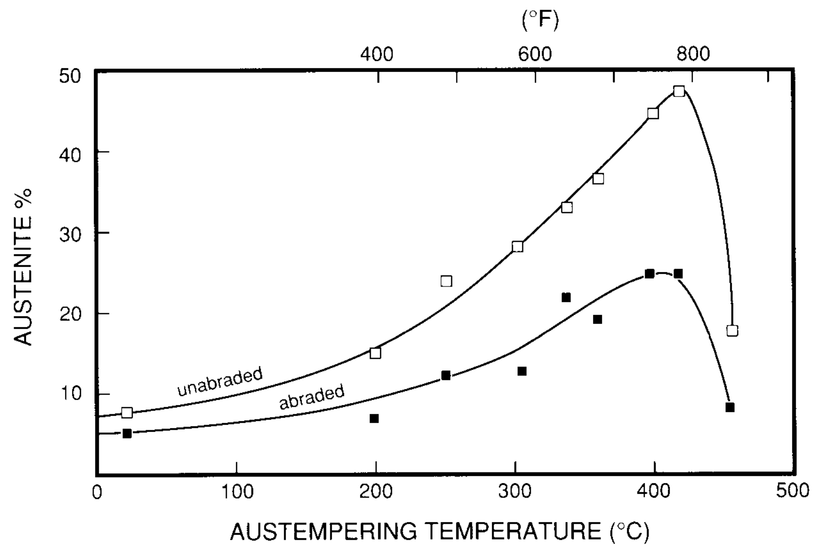


Microhardness scan of an abraded ADI sample.

SECTION IV

Figure 4.26). This increase in austenite content increases the hardness increment produced by surface deformation. As a result, a Ductile Iron component austempered to produce a lower hardness displays an abrasion resistance greater than that predicted by its bulk hardness, provided that the abrasion mechanism involves sufficient deformation to transform the surface layers to martensite.

Figure 4.26



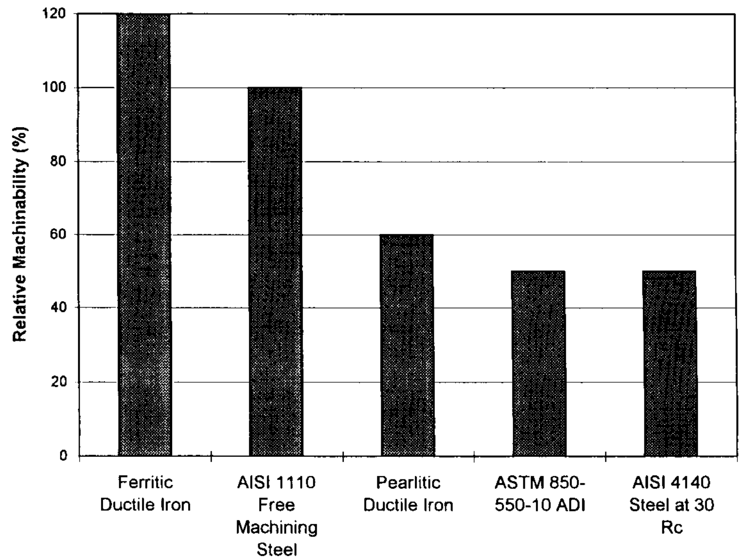
Relationship between the austempering temperature and the amount of stabilized austenite surface of abraded and unabraded ADI samples.

Through variations in austempering conditions, the designer can optimize the abrasion resistance and related mechanical properties of an ADI component. For a combination of high toughness and abrasion resistance an austempering temperature in the range of 650-700°F (350-375°C) should be used. When a combination of high strength and abrasion resistance are required, an austempering temperature of 500°F (260°C) will yield the best results.

Machinability

Compared to competitive materials, the machinability of Ductile Iron has been one of its major advantages. When the substantial increases in strength and wear resistance offered by ADI are considered, it would be logical to assume that ADI could present machining problems. However, cost savings in machining are frequently mentioned as reasons for converting to ADI. The reasons for this surprising combination of mechanical properties and machinability are two-fold. First, the machinability of the softer grades of ADI is equal or superior to that of steels with equivalent strength, and second, the predictable growth characteristics of ADI during austemper heat treatment allow, in many cases, for it to be machined complete in the soft as-cast or annealed state before heat

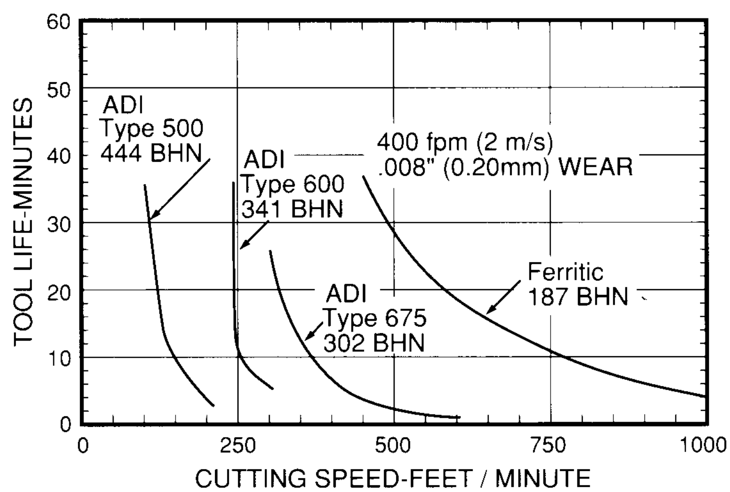
Figure 4.27



Relative machinability of several ferrous materials.

SECTION IV

Figure 4.28

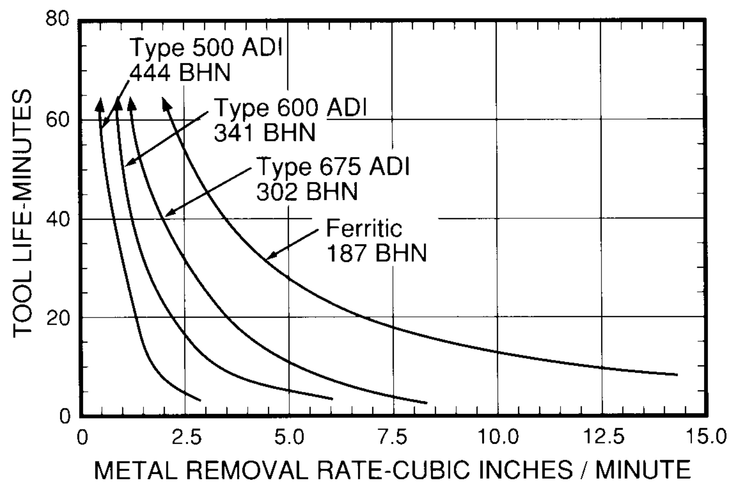


Effect of cutting tool speed and the hardness of different ADI samples on tool life.

Note: The ADI Types (500, 600, 675) in these Figures refer to the austempering temperature in °F. (See Figure 4.13) treatment. This allows for faster machine feeds and speeds and greatly increased tool life. (See Figure 4.27).

As discussed in a later section on surface deformation treatments of gears, the processing of ADI parts should could follow one of several paths, (Figure 4.34), depending primarily on the grade of ADI, but also on the surface treatment benefits that may be gained from machining after austempering. As shown in Figures 4.28 and 4.29, cutting tool life

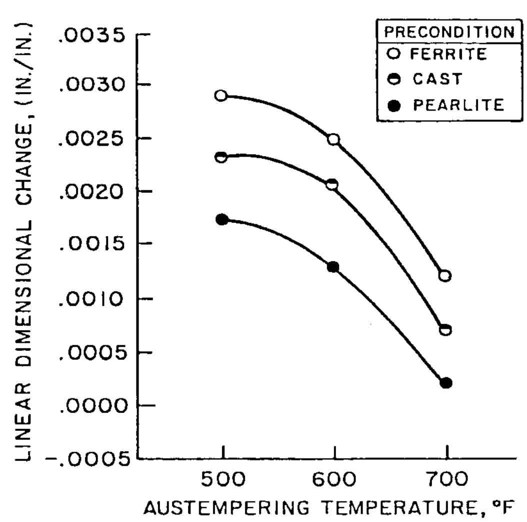
Figure 4.29



Effect of metal removal rate and the hardness of different ADI samples on tool life.

SECTION IV

Figure 4.30



Linear dimensional change as a function of austempering temperature*.

* EACH POINT REPRESENTS AVERAGE OF 12 POINTS (1 EACH ALLOY)

Table 4.4

Tool life improvement resulting from the replacement of case-carburized forged steel gears with ADI.

Machining operation	Tool-life improvement %
Pinion blanking	
– centre press	30
– drill	35
– rough lathes	70
– finish lathes	50
– grind	20
Rear-gear blanking	
– bullard turning	200
– drilling	20
– reaming	20
Gleason machining	
– pinion – roughing	900
– finishing	233
– ring – roughing	962
– finishing	100

SECTION IV

Table 4.5

Guidelines for the machining of a lower strength grade of ADI.

Machining operation	Tools	Cutting speed, m/min	Feed, mm/revolution
Turning	K20 bits with TiC angle $\gamma = -6°$, no cutting-oil, tool force 1.6 – 1.8 kN/mm²	50 – 70	Roughing: 0.5 – 1.0 Finishing: 0.15 – 0.3
Drilling	Carbide-tipped drills	12 – 15	0.05 – 0.12
Keyway broaching	High-speed steel, $\gamma = 10°$, $\alpha = 5°$ with cutting-oil	3 – 6	0.05 – 0.08
Hobbing	Hobs flooded with cutting-oil	8 – 20	1.5 – 2.5 depending on module
Grinding	Grade 37C16-P4B wheels		

Table 4.6

Recommended machining conditions for a lower strength grade of low-manganese ADI.

	Turning		Driling	
Machining	High-speed steel	SiN_2	High-speed steel	Carbide
Cutting-speed, m/min	100	100	20	50
Feed, mm	0.355	0.25	0.25	0.18
Depth of cut, mm	2	4	12.5 dia	11.5 dia
Wear, mm	0.7	0	–	–
Tool life, min	12	>10	20	25
Lubrication	Yes	Yes	Yes	Yes

decreases substantially as the hardness of ADI increases and the cutting speed and metal removal rate increase. For these reasons, only the 125/80/10 and 150/100/07 grades of ADI should be machined after austempering. Parts processed to the higher strength grades should receive the following processing sequence:

1. Cast the component
2. (Optionally) subcritically anneal to a fully ferritic matrix
3. Machine
4. Austemper
5. Finish machine (if required)
6. Finish operations (rolling, grinding, peening, if required)

While annealing adds cost to the casting the benefits of more predictable dimensional change during austempering and greatly improved machinability often more then offset the cost of annealing. In order to obtain the benefits of the excellent machinability of annealed Ductile Iron, the designer must have confidence in the reproducibility of the growth of the machined casting during heat treatment. Papers presented at the 1st International Conference on ADI indicated that dimensional changes during heat treatment varied from a slight contraction to a growth of approximately 0.4%, (Figure 4.30). It was stressed that as long as the prior Ductile Iron microstructure was consistent in pearlite/ferrite ratio, predictable growth occured and close tolerance ADI parts could be produced successfully by machining prior to heat treatment.

The production of ADI ring and pinion gear sets for General Motors rear wheel drive cars (model years 1977-1979) provides a good example of the reduction in machining costs offered by ADI. As shown in Table 4.4, tool life improvement for different machining operations performed on the ferritized ADI blanks ranged from 20% to over 900% compared to similar operations required to produced the forged, carburized and hardened 8620 steel gears that they replaced. The overall cost savings to GM of converting from carburized steel to austempered ring and pinion gears was approximately 20%.

Tables 4.5 and 4.6 provide guidelines for the machining of the lower strength grades of ADI. In general, reduced surface speeds and increased feed rates provide the best metal removal rate in ADI.

Production Control

The mechanical properties offered by ADI make it an attractive material for demanding applications in which strict specifications must be met consistently. While greatly enhancing the properties of a conventional Ductile Iron casting, the ADI process cannot compensate for casting

Effects of carbon, silicon and the major alloying elements an austempering behavior.

Table 4.7

Carbon	Increasing carbon in the range 3 to 4% increases the tensile strength but has negligible effect on elongation and hardness. Carbon should be controlled within the range 3.6-3.8% except when deviations are required to provide a defect-free casting.
Silicon	Silicon is one of the most important elements in ADI because it promotes graphite formation, decreases the solubility of carbon in austenite, increases the eutectoid temperature, and inhibits the formation of bainitic carbide. Increasing the silicon content increases the impact strength of ADI and lowers the ductile-brittle transition temperature. Silicon should be controlled closely within the range 2.4-2.8%.
Manganese	Manganese can be both a beneficial and a harmful element. It strongly increases hardenability, but during solidification it segregates to cell boundaries where it forms carbides and retards the austempering reaction. As a result, for castings with either low nodule counts or section sizes greater than 3/4 in. (19mm), manganese segregation at cell boundaries can be sufficiently high to produce shrinkage, carbides and unstable austenite. These microstructural defects and inhomogeneities decrease machinability and reduce mechanical properties. To improve properties and reduce the sensitivity of the ADI to section size and nodule count, it is advisable to restrict the manganese level in ADI to less than 0.3%. The use of high purity pig iron in the ADI charge offers the twin advantages of diluting the manganese in the steel scrap to desirable levels and controlling undesirable trace elements.
Copper	Up to 0.8% copper may be added to ADI to increase hardenability. Copper has no significant effect on tensile properties but increases ductility at austempering temperatures below 675°F (350°C).
Nickel	Up to 2% nickel may be used to increase the hardenability of ADI. For austempering temperatures below 675°F (350°C) nickel reduces tensile strength slightly but increases ductility and fracture toughness.
Molybdenum	Molybdenum is the most potent hardenability agent in ADI, and may be required in heavy section castings to prevent the formation of pearlite. However, both tensile strength and ductility decrease as the molybdenum content is increased beyond that required for hardenability. This deterioration in properties is probably caused by the segregation of molybdenum to cell boundaries and the formation of carbides. The level of molybdenum should be restricted to not more than 0.2% in heavy section castings.

defects that would impair mechanical properties. ADI castings should, therefore, be produced free from surface defects, and with the following microstructural parameters.

- Nodularity: >80% type I and II nodules
- Nodule Count: 100/mm^2 minimum
- Consistent chemical composition
- Essentially free of carbides, porosity and inclusions
- Consistent pearlite/ferrite ratio

These requirements are essentially the same those required to produce good quality Ductile Iron. To assure quality, ADI should be purchased from casting and heat treatment suppliers that have well developed process control systems who can demonstrate that they are consistently capable of producing high quality castings and heat treatments.

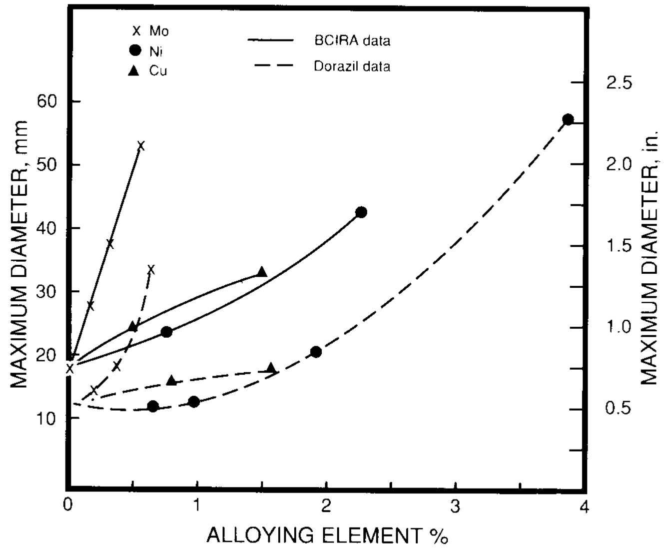
The production of a high quality casting is essential but, by itself, not a sufficient condition to ensure optimum properties in ADI. The casting must be heat treated properly by a supplier capable of taking into account the interaction between casting dimensions, composition, microstructure and the desired properties in the austempered casting. For this reason, there should be close cooperation between the designer, metal caster, heat treater and machine source from conception of the design to delivery of the castings.

Composition

In many cases, the composition of an ADI casting differs little from that of a conventional Ductile Iron casting. When selecting the composition, and hence the raw materials, for both conventional Ductile Iron and ADI, consideration should be given first to limiting elements which adversely affect casting quality through the production of non-spheroidal graphite, or the formation of carbides and inclusions, or the promotion of shrinkage. The second consideration is the control of carbon, silicon and the major alloying elements (See Table 4.7) that control the hardenability of the iron and the properties of the transformed microstructure. When determining the alloying requirements both the section size and type and the severity (or speed) of the austempering quench must be considered.

For a typical salt quench with agitation section sizes up to about 3/8 inch (10 mm) can be successfully through hardened without pearlite with even unalloyed Ductile Iron. For a highly agitated austemper quench with water saturation section sizes of up to 3/4 inch (20 mm) can be through hardened with no additional alloying. For castings of heavier section size selective alloying is required to through harden the parts and avoid pearlite in the heat treated microstructure.

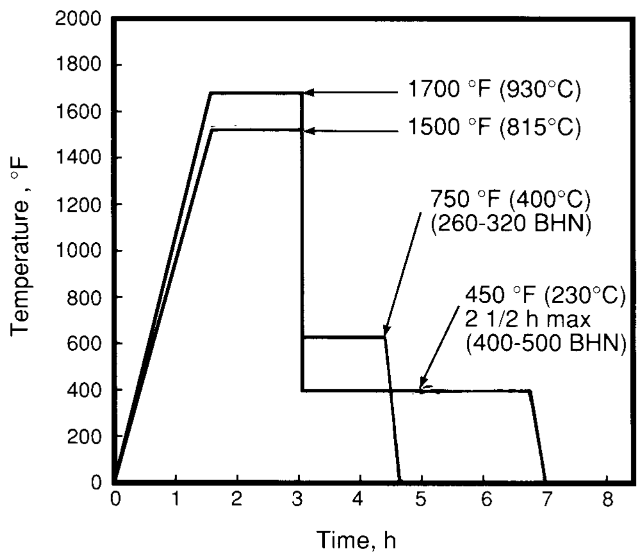
Figure 4.31



The effect of nickel, copper and molybdenum contents on the maximum diameter which can be austempered at 350°C (600°F) without pearlite formation.

SECTION IV

Figure 4.32



Typical austempering cycles for different grades of ADI.

Figure 4.31 summarizes the hardenability of copper, nickel and molybdenum by relating the levels of these elements to the maximum diameter bar that can be satisfactorily austempered. (The BCIRA data utilizes a relatively fast quench while the Dorazil data reflects an austempering bath with a lower quench severity). The relative hardenability contribution of manganese is between that of molybdenum and copper.

Alloy Combinations

For economic reasons, or to avoid metallurgical problems, combinations of alloys are often used to achieve the desired hardenability in ADI. To avoid micro-segregation and the resultant degradation of mechanical properties associated with higher levels of manganese and molybdenum, their levels should be carefully controlled with the desired hardenability obtained by supplementary additions of first copper (up to about 0.8%), then nickel.

The Role of Alloys in ADI

The primary purpose of adding copper, nickel or molybdenum to ADI is to increase the hardenability of the matrix sufficiently to ensure that the formation of pearlite is avoided during the austempering process. These elements have only marginal effect on the mechanical properties of ADI that is properly austempered. (The austempering process determines the properties after austempering; not the alloying). Only the minimum amount of alloys required to through harden the part should be employed. Excessive alloying only increases the cost and difficulty of producing the good quality Ductile Iron necessary for ADI. Ultimately, the amount of alloying required will be a function of the metal caster's base composition, the casting section size and type and the characteristics of the chosen heat treatment process.

SECTION IV

A typical iron composition (and control range) that can be used is shown below:

Carbon*	3.7%	+/- 0.2%	
Silicon*	2.5%	+/- 0.2%	
Manganese	0.20%	+/- 0.03%	
Copper	as required	+/- 0.05%	up to 0.8% maximum
Nickel	as required	+/- 0.10%	up to 2.0% maximum
Molybdenum	only if required	+/- 0.03%	up to 0.25% maximum

* (Carbon and silicon shoud be controlled to produce the desired carbon equivalent for the section size being produced).

The aforementioned composition does not guarantee ADI properties, nor is it mandatory. However, this composition is a typical, industrially successful ADI composition. A good controlled chemistry like this one combined with a consistently high nodule count and nodularity and a consistent pearlite/ferrite ratio in clean, shrink-free Ductile Iron will provide the most robust process for the production of ADI.

Heat Treatment

ADI is produced by an isothermal heat treatment know as austempering. Austempering consists of the following steps as shown in Figure 4.32:

1. Heating the casting to the austenitizing temperature in the range of 1500-1700°F (815-927°C).

Figure 4.31 summarizes the hardenability of copper, nickel and molybdenum by relating the levels of these elements to the maximum diameter bar that can be satisfactorily austempered. (The BCIRA data utilizes a relatively fast quench while the Dorazil data reflects an austempering bath with a lower quench severity). The relative hardenability contribution of manganese is between that of molybdenum and copper.

Alloy Combinations

For economic reasons, or to avoid metallurgical problems, combinations of alloys are often used to achieve the desired hardenability in ADI. To avoid micro-segregation and the resultant degradation of mechanical properties associated with higher levels of manganese and molybdenum, their levels should be carefully controlled with the desired hardenability obtained by supplementary additions of first copper (up to about 0.8%), then nickel.

The Role of Alloys in ADI

The primary purpose of adding copper, nickel or molybdenum to ADI is to increase the hardenability of the matrix sufficiently to ensure that the formation of pearlite is avoided during the austempering process. These elements have only marginal effect on the mechanical properties of ADI that is properly austempered. (The austempering process determines the properties after austempering; not the alloying). Only the minimum amount of alloys required to through harden the part should be employed. Excessive alloying only increases the cost and difficulty of producing the good quality Ductile Iron necessary for ADI. Ultimately, the amount of alloying required will be a function of the metal caster's base composition, the casting section size and type and the characteristics of the chosen heat treatment process.

A typical iron composition (and control range) that can be used is shown below:

Carbon*	3.7%	+/- 0.2%	
Silicon*	2.5%	+/- 0.2%	
Manganese	0.20%	+/- 0.03%	
Copper	as required	+/- 0.05%	up to 0.8% maximum
Nickel	as required	+/- 0.10%	up to 2.0% maximum
Molybdenum	only if required	+/- 0.03%	up to 0.25% maximum

* (Carbon and silicon shoud be controlled to produce the desired carbon equivalent for the section size being produced).

The aforementioned composition does not guarantee ADI properties, nor is it mandatory. However, this composition is a typical, industrially successful ADI composition. A good controlled chemistry like this one combined with a consistently high nodule count and nodularity and a consistent pearlite/ferrite ratio in clean, shrink-free Ductile Iron will provide the most robust process for the production of ADI.

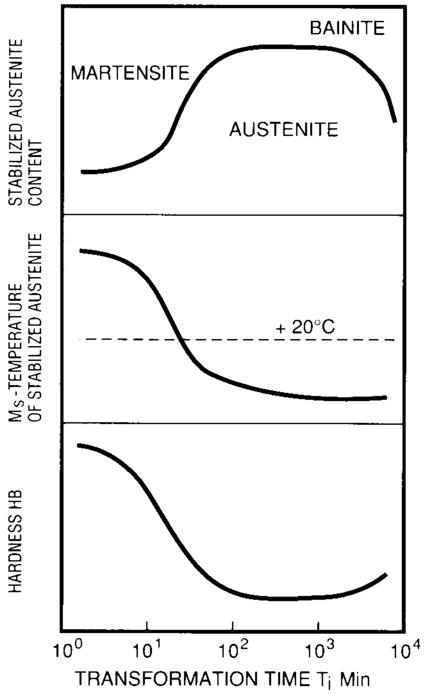
Heat Treatment

ADI is produced by an isothermal heat treatment know as austempering. Austempering consists of the following steps as shown in Figure 4.32:

1. Heating the casting to the austenitizing temperature in the range of 1500-1700°F (815-927°C).

SECTION IV

Figure 4.33



Schematic diagram showing the effect of austempering time on the amount and stability of austenite and the hardness of ADI.

Courtesy of Applied Process Inc.

Assorted ADI conveyor components.

2. Holding the part at the austenitizing temperature for a time sufficient to get the entire part to temperature and to saturate the austenite with carbon.

3. Quenching (cooling) the part rapidly enough to avoid the formation of pearlite to the austempering temperature in the range of 450-750°F (232-400°C). (This temperature is above the martensite start temperature (Ms) for the material).

4. Austempering the part at the desired temperature for a time sufficient to produce a matrix of ausferrite. (That is a matrix of acicular ferrite and austenite stabilized with about 2% carbon).

5. Cooling the part to room temperature.

The austenitizing may be accomplished by using a high temperature salt bath, an atmosphere furnace or (in special cases) a localized method such as flame or induction heating. The austempering is most typically carried out in a nitrite/nitrate salt bath but in special cases it can be accomplished in hot oil (up to 470°F (243°C)), or molten lead or tin.

The critical characteristics are:

- The austenitizing time and temperature
- A cooling rate sufficient for the casting/alloy combination
- The austempering time and temperature

SECTION IV

Austenitizing

The austenitizing temperature controls the carbon content of the austenite which, in turn, affects the structure and properties of the austempered casting. High austenitizing temperatures increase the carbon content of the austenite, increasing its hardenability, but making transformation during austempering more problematic and potentially reducing mechanical properties after austempering. (The higher carbon austenite requires a longer time to transform to ausferrite). Reduced austenitizing temperatures generally produce ADI with the best properties but this requires close control of the silicon content, which has a significant effect on the upper critical temperature of the Ductile Iron.

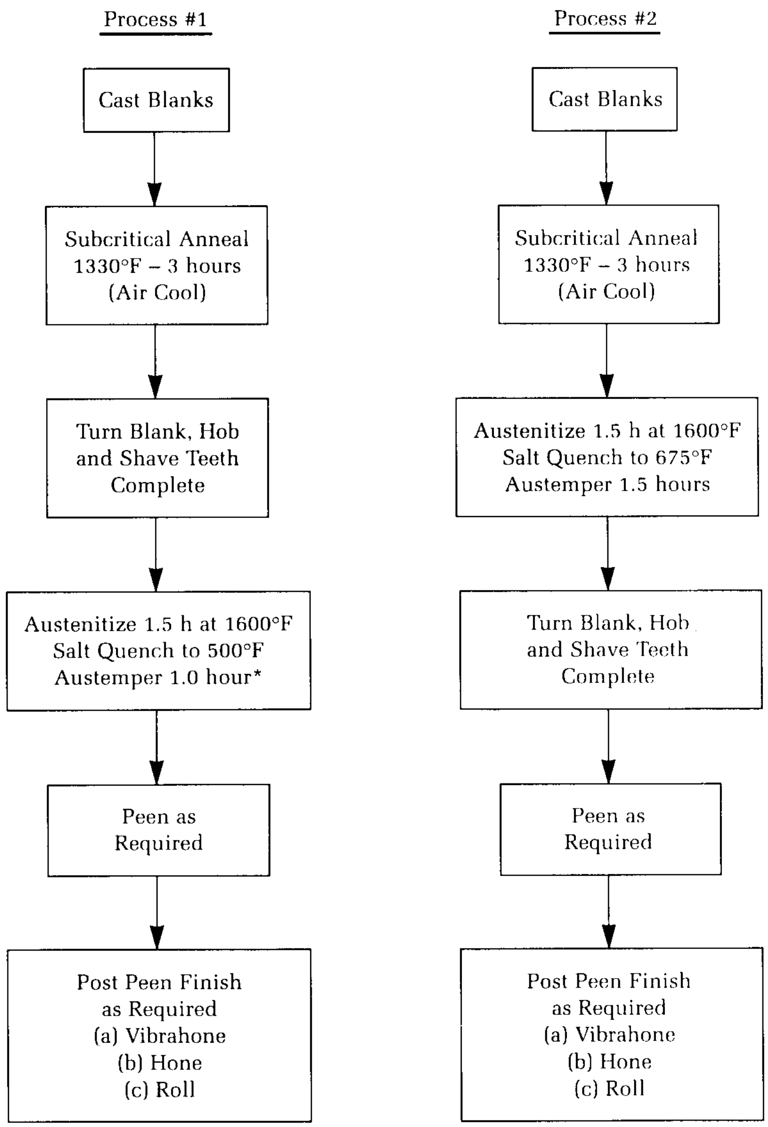
Austenitizing time should be the minimum required to heat the entire part to the desired austenitizing temperature and to saturate the austenite with the equilibrium level of carbon, (typically about 1.1-1.3%). In addition to the casting section size and type, the austenitizing time is affected by the chemical composition, the austenitizing temperature and the nodule count.

Austempering

Austempering is fully effective only when the cooling rate of the quenching apparatus is sufficient for the section size and hardenability of the component. The minimum rate of cooling is that required avoid

Flow charts for the processing of different grades of ADI (gears).

Figure 4.34



the formation of pearlite in the part during quenching to the austempering temperature. The critical characteristics are as follows:

- Transfer time from the austenitizing environment to the austempering environment
- The quench severity of the austempering bath
- The maximum section size and type of casting being quenched
- The hardenability of the castings
- The mass of the load relative to the quench bath.

The use of a correctly designed austempering system with a suitably high quench severity, and the correct loading of castings, can minimize hardenability requirements of the casting resulting in significant savings in alloy costs.

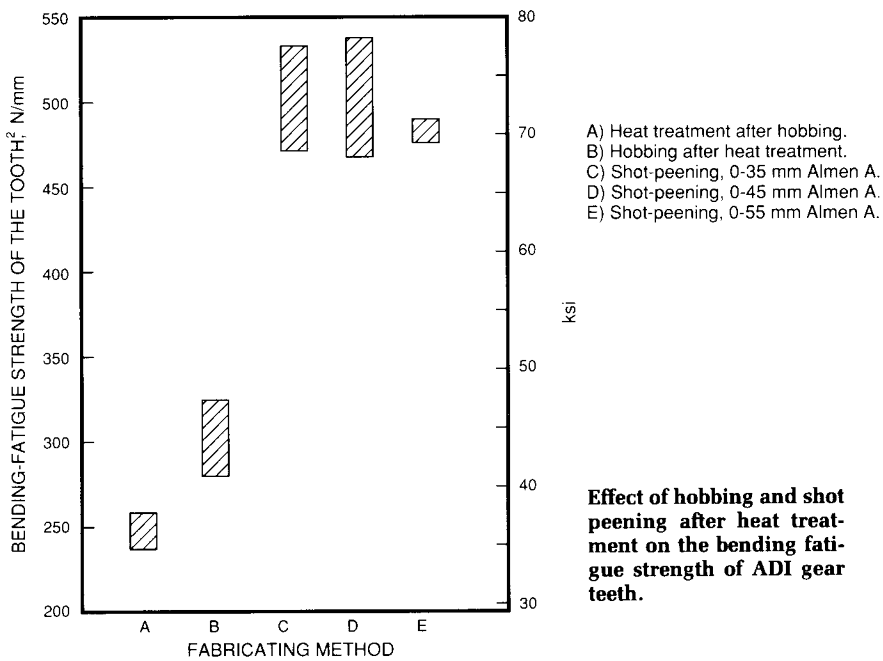
As illustrated earlier in Figure 4.6, austempering temperature is one of the major determinants of the mechanical properties of ADI castings. To produce ADI with lower strength and hardness but higher elongation and fracture toughness, a higher austempering temperature (650-750°F (350-400°C)) should be selected to produce a coarse ausferrite matrix with higher amounts of carbon stabilized austenite (20-40%). Grades 125/80/10 and 150/100/07 would be typical of these conditions. To produce ADI with higher strength and greater wear resistance, but lower fracture toughness, austempering temperatures below 650°F (350°C) should be used.

Once the austempering temperature has been selected, the austempering time must be chosen to optimize properties through the formation of a stable structure of ausferrite. Figure 4.33 schematically illustrates the influence of austempering time on the stabilization of austenite, and shows the hardness of the resultant matrix. At short austempering times, there is insufficient diffusion of carbon to the austenite to stabilize it, and martensite may form during cooling to room temperature. The resultant microstructure would have a higher hardness but lower ductility and fracture toughness (especially at low temperatures). Excessive austempering times can result in the decomposition of ausferrite into ferrite and carbide (bainite) which will exhibit lower strength, ductility and fracture toughness. At the highest austempering temperature (750°F (400°C)) as little as 30 minutes may be required to produce ausferrite. At 450°F (230°C) as much as four hours may be required to produce the optimum properties; Figure 4.32.

Note: a strength level maxima is achieved in ADI at an austempering temperature of about 475-525°F (250-275°C). At temperatures below that range the hardness may increase but the strength may decrease due to the presence of martensite mixed in with the ausferritic matrix. (In other words, as the austempering temperature is incrementally decreased below 475°F (250°C) the material behaves increasingly like a quenched and tempered Ductile Iron).

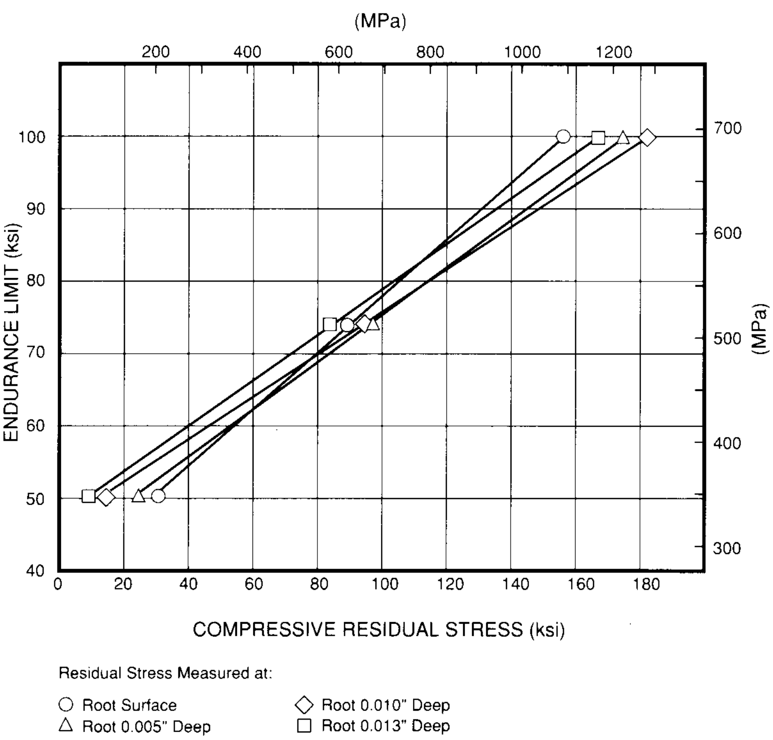
SECTION IV

Figure 4.35



Effect of hobbing and shot peening after heat treatment on the bending fatigue strength of ADI gear teeth.

Figure 4.36



Relationship between residual peening stress and endurance limit for peened ADI gears.

SECTION IV

Surface Deformation Treatments

The austempering treatment used to produce ADI can result in small residual tensile surface stresses. Even so, ADI has excellent fracture toughness and fatigue strength. However, ADI's ability to resist the initiation of fatigue cracks (especially in cyclic bending) may be greatly enhanced by inducing compressive stresses to the surface after the austemper heat treatment.

These small tensile stresses can be easily replaced with rather substantial compressive stresses if the ADI is subjected to any surface treatment involving the sufficient surface deformation to cause a strain-induced transformation of the stabilized austenite. Such treatments could include conventional machining operations such as turning, grinding, milling, hobbing or special treatments such as shot peening or surface rolling.

For parts subjected to fatigue failure, performance can be enhanced significantly if machining operations can be performed after austempering. However, this processing sequence is limited by the machinability of the different grades of ADI. Figure 4.34 shows the two processing flow charts used by the ASME Gear Research institute to produce ADI test gears. Using machinability as the main criterion, the GRI selected process #2 for blanks with heat treated hardnesses in the range of 30-34 HRC and process #1 for blanks with hardness greater than 37 HRC. Figure 4.35 reveals that hobbing after austempering resulted in a 20% increase in fatigue strength of gear teeth.

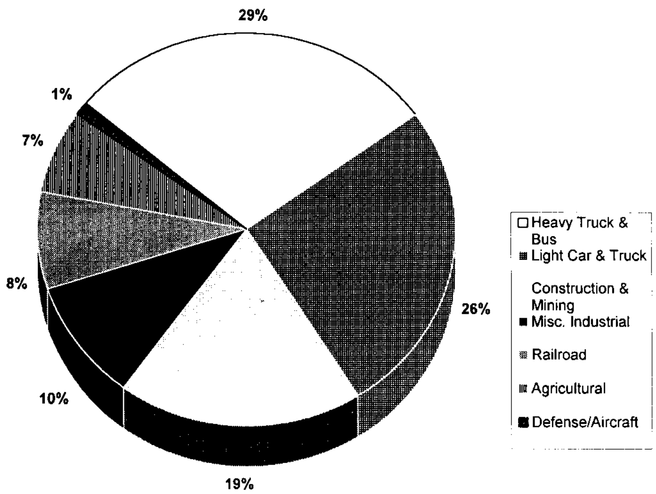
Shot Peening

Shot peening offers a controllable means of selectively hardening certain parts of a finished casting to produce significant improvements in fatigue properties. Figure 4.35 shows that shot peening a hobbed gear increased fatigue strength by 60%. Single tooth fatigue tests conducted by the GRI on ADI gears indicated that shot peening doubled the fatigue strength. The GRI work also identified a significant correlation between residual compressive stress produced by peening and the endurance limit (Figure 4.36). In addition to being able to be applied to selected areas of a part, peening also offers the advantage of increasing surface hardness without detrimentally affecting the ductility and strength of the remainder of the component. Post peening surface treatments such as honing may be required to reduce surface roughness in parts subjected to rolling contact fatigue. (For more information see Section IX.)

Surface Rolling

Surface rolling or burnishing produced with a hardened roller, or mating part in the case of gear hardening, may be used independently or as a post-peening operation to improve the fatigue properties of ADI. Gear Research Institute tests show that roll burnishing of a peened gear with a carburized steel mate produced a six-fold increase in fatigue life. Fillet rolling has been used very effectively to offset reductions in fatigue life produced by stress concentrations at changes in cross section in castings such as crankshafts and gear clusters (see Table 3.3 and Section IX).

Figure 4.37



Estimated distribution of North American ADI market (as of 1998).

Table 4.8

Comparison of energy requirements for the production of ADI and forged and carburized steel gears.

Operation	Energy consumption kWh per Tonne ADI	Forged steel
Production of blank	2,500	4,500
Annealing		500
Austempering	600	—
Case-hardening	—	800-1,200
Total	3,100	5,800-6,200

Table 4.9

ASTM 897 (in-lb units)	125 80 10	150 100 07	175 125 04	200 155 01	230 185 00
ASTM 897M (SI units)	850 550 10	1050 700 07	1200 850 04	1400 1100 01	1600 1300 00
"Grade"	1	2	3	4	5
Property					
Min. Tensile Strength (ksi/MPa)	125/850	150/1050	175/1200	200/1400	230/1600
Min. 0.2% Offset Yield Strength (ksi/MPa)	80/550	100/700	125/850	155/1100	185/1300
Min. Elongation (% in 2 in/50mm gage)	10	7	4	1	n/a
Typical Brinell Hardness (BID mm)	302 (3.50)	340 (3.30)	387 (3.10)	418 (3.00)	460 (2.85)
Typical Density (lb/in^3 / g/ cm^3)	.2562/7.0965	.2558/7.0872	.2555/7.0779	.2552/7.0686	.2548/7.0593
Typical Thermal expansion (in/in/F / mm/mm/C)	8.1/14.6	8.0/14.3	7.8/14.0	7.7/13.8	7.5/13.5
Typical Thermal conductivity (BTU-in/h-ft^2 / W-MK)	153/22.1	151/21.8	149/21.5	147/21.2	145/20.9
Typical Internal Damping (log decrement X .0001)	5.26	5.41	5.69	12.7	19.2

Other Properties

There are many properties needed for specific design applications that are not currently published. Without these important properties engineers must make assumptions about a material's behavior and mistakes can be made, (as discussed in some of the referenced papers listed in this chapter). Table 4.9 summarizes some of those properties for the five ASTM 897 grades.

Applications

The development and commercialization of Austempered Ductile Iron (ADI) has provided the design engineer with a new group of cast ferrous materials which offer the exceptional combination of mechanical properties equivalent to cast and forged steels and production costs similar to those of conventional Ductile Iron. In addition to this attractive performance: cost ratio, ADI also provides the designer with a wide range of properties, all produced by varying the heat treatment of the same castings, ranging from 10-15% elongation with 125 ksi (870 MPa) tensile strength, to 250 ksi (1750 MPa) tensile strength with 1-3% elongation. Although initially hindered by lack of information on properties and successful applications, ADI has become an established alternative in many applications that were previously the exclusive domain of steel castings, forgings, weldments, powdered metals and aluminum forgings and castings.

The ADI market represents nearly all segments of manufacturing. Figure 4.37 shows the approximate breakdown of the North American ADI market.

Heavy Truck and Bus Components

Heavy truck applications include suspension components such as spring hanger brackets, shock brackets, u-bolt plates, wheel hubs, brake calipers and spiders, knuckles, sway bar components, pintle hooks and gears for trailer landing gear. Powertrain related ADI heavy truck and bus components include engine brackets and mounts, timing gears, cams, annular gears, differential gears and cases, clutch collars, accessory brackets and pulleys.

Light Auto and Truck Components

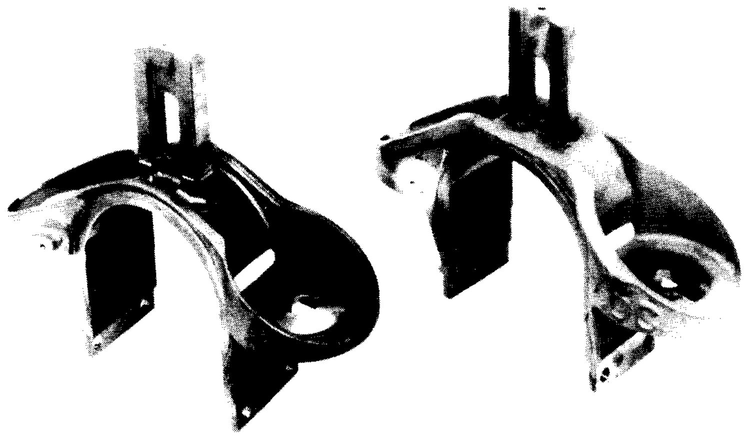
Light vehicle ADI applications include suspension components, knuckles, spindles, hubs, tow hooks, hitch components, differential gears and cases, engine and accessory brackets, camshafts, engine mounts, crankshafts and control arms. Constant velocity joints for four wheel drive GM vehicles have been produced in ADI since 1978 and currently run at volumes of over 5,000 per day.

Construction and Mining Components

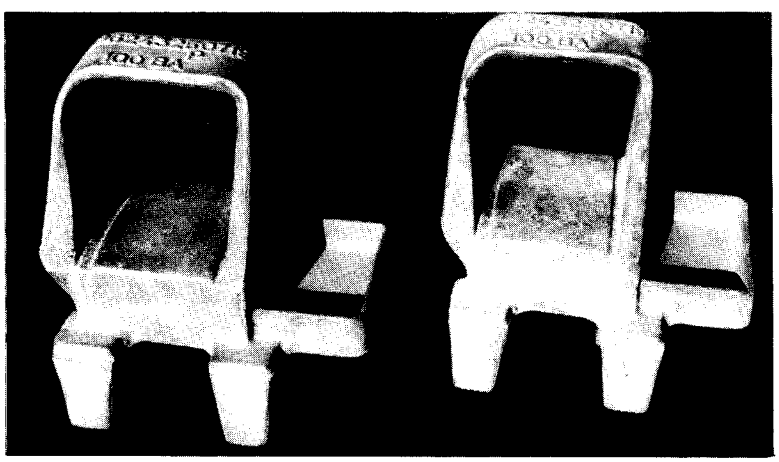
This segment includes all manner of collets, ring carriers, wear plates, sprockets, covers, arms, knuckles, shafts, rollers, track components, tool holders, digger teeth, cutters, mill hammers, cams, sway bars, sleeves, pavement breaker bodies and heads, clevises, and conveyor components.

Miscellaneous Industrial

Miscellaneous industrial applications include brackets, lever arms, knuckles, shafts, cams, sway bars, sleeves, clevises, conveyor components, jack components, bushings, rollers, molding line components, fixtures, gears, sprockets, deck plates, and all sorts of power transmission and structural components.



Railway axle-spring adaptor (by courtesy of SKP Sweden).
Left: ADI (Muhlberger GGG100B/A).
Weight: 29,7 kg.
Right: SG iron GGG80. Weight: 42 kg.
Weight savings with ADI = 12 kg (30%).



Truck spring support in ADI which replaced cast steel (Muhlberger GGG100B/A).

Railroad

The railroad industry uses ADI for suspension housings, top caps and friction wedges, track plates, repair vehicle wheels, nipper hooks, and car wheels.

Agricultural

Farming and agricultural applications for ADI include plow points, till points, trash cutters, seed boots, ammonia knives, gears, sprockets, knotter gears, ripper points, tractor wheel hubs, rasp bars, disk parts, bell cranks, lifting arms, and a great variety of parts for planters, plows, sprayers and harverters.

Defense

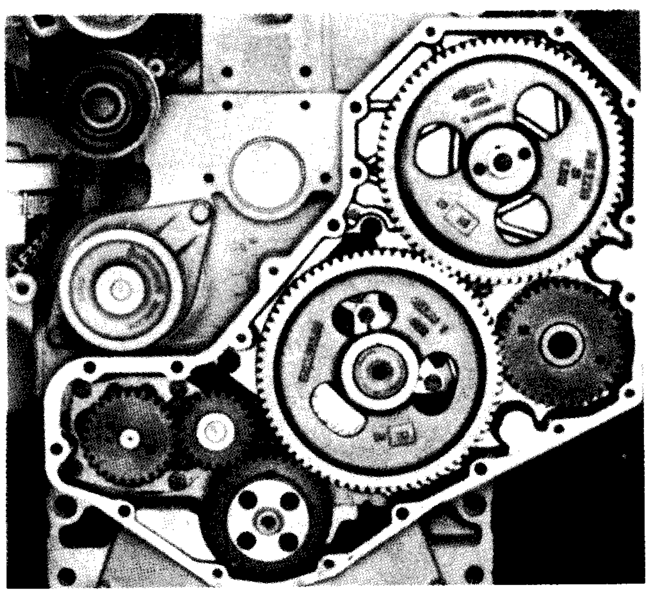
The defense industry has been relatively slow to adopt ADI, however some of the applications include track links, armor, ordnance and various hardware for trucks and armored vehicles.

Special Product Categories

Gears

Gears represent some of the best known, most widely publicized and high potential uses of ADI. During the early 1970's the Finnish company Kymi Kymmene Metall began to replace forged steel with ADI in a in a wide range of gears, with highly satisfactory results.

In North America, ADI achieved a major breakthrough in 1977, when General Motors converted a forged and case hardened steel ring gear and pinion to ADI for Pontiac rear drive cars and station wagons. The decision came after nine years of development work and six years of field testing. The automaker was able to gain both significant cost savings and product improvement by changing to ADI.



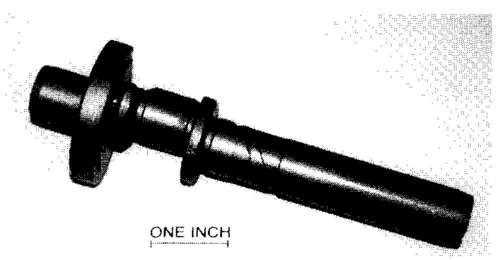
ADI Timing Gears for Cummins B-Series diesel engines. Replaced forged and case carburised 1022 steel with 30% cost saving.

Courtesy of Applied Process Inc.

An assortment of ADI "ground engaging" parts.

Courtesy of Applied Process Inc.

ADI crawler type track shoe.



Courtesy of Wagner Castings and Tecumsen Products.

ADI crankshaft for a hermetically sealed compressor (first produced in 1972).

In 1983, the Cummins Engine Co. began to use ADI timing gears, produced to AGMA class 8 standards, in its B and C series diesel engines. These gears were machined and hobbed from annealed Ductile Iron castings. A crown shaving operation was carried out on the gear teeth prior to austempering, and the only operations performed after austempering were the grinding of the bore diameter and shot peening. Annual production exceeds 30,000 sets and the cost savings are estimated at 30% compared to the forged and carburized 1022 steel gears previously used.

Table 4.8 describes the energy savings of almost 50% resulting from the conversion to ADI gears. In addition to savings in energy and overall production costs, ADI gears offer the following advantages:

- increased machine shop productivity
- reduction in weight of up to 10%
- reduced gear noise
- rapid "break in" of new gears and,
- improved resistance to scoring.

Crankshafts

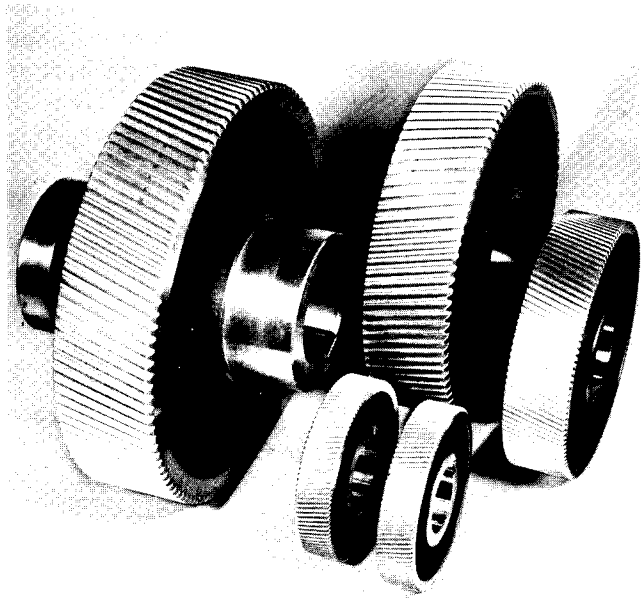
Crankshafts are another potentially significant application for Austempered Ductile Iron. The first commercially produced ADI part was a small crankshaft for a hermetically sealed refrigerator compressor. It was cast by Wagner Castings Company (US) for Tecumseh Products. Production of that part was initiated in 1972 and since that time, millions of those crankshafts have been produced.

Engines being developed by the automotive industry require weight reduction in parts that will be required to handle increased power. Automotive design engineers have evaluated ADI as a candidate for both the replacement of forged steel crankshafts and the upgrading of existing Ductile Iron crankshafts. The Ford Motor Company made an exhaustive, three year study of ADI crankshafts and concluded that they met all design criteria. During this study, the importance of fatigue testing was identified, and the following results were obtained:

Fatigue Test Method	**Fatigue Strength**	
	ksi	**MPa**
Constant Strain Amplitude	55	380
Rotating Bending	65	450
Reversed Bending	60	415
Reversed Bending (fillet rolled)	90	620

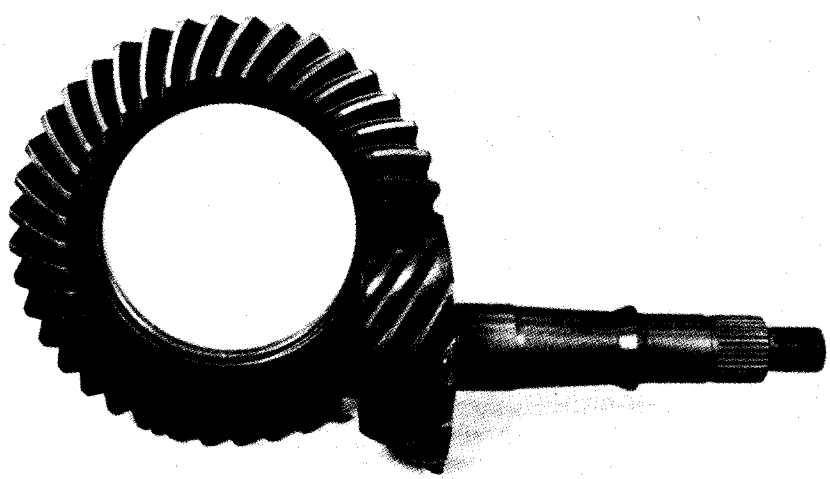
A thorough, joint Motor Industry Research Association/Cast Metals Development Laboratories study on ADI crankshafts concluded that properly fillet rolled ADI crankshafts exhibited fatigue properties comparable to, or better than, the best forged and heat treated steel crankshafts.

SECTION IV



Courtesy: Kymi Kymmene Engineering, Finland.

Austempered Ductile Iron gears to patented specifications K9805.



Courtesy: General Motors Corp. Central Foundry Div.,
Saginaw, Michigan, USA

Austempered Ductile Iron Hypoid Axle Gears: Conversion to Cast Ductile Iron from Forged Steel gave: major production cost saving, better machinability, quieter operation, reduced weight.

In another documented crankshaft study conducted at the Manchester (England) Materials Science Center, the authors demonstrated the performance capability of ADI crankshafts in one cylinder commercial and four cylinder automotive engines. They noted a 10% rotating weight reduction and an estimated 30% cost savings.

As of this writing ADI crankshafts are employed in high volume commercial applications and low volume automotive applications. As the specific power requirements for automotive engines are increased, ADI will become a more viable alternative to the heavier, more expensive forged steel crankshaft.

Conclusion

As design engineers become more familiar with ADI's strength, toughness, wear resistance and noise damping properties and learn about the impressive cost and weight savings reported in successful ADI conversions from steel castings, weldments and forgings and aluminum castings and forgings, ADI will continue its remarkable growth.

SECTION IV

REFERENCES

E. Dorazil, "Mechanical Properties of Austempered Ductile Iron", Foundry Management & Technology, July, 1986, 36-45.

T. Luyendijk and H. Nieswaag, "The Influence of Silicon on the Toughness of Bainitic Ductile Iron." Proceedings of the 50th International Foundry Conference, Cairo, 1983.

A Design Engineer's Digest of Ductile Iron, 5th Edition, QIT-Fer et Titane Inc., Montreal, Quebec, Canada, 1983.

"Ductile Iron," Foundry Management & Technology, September, 1989.

R. A. Harding, "Effects of metallurgical process variables on austempered ductile irons," Metallurgical Materials, 1986.

D. J. Moore, K. B. Rundman, and T. N. Rouns, "The effect of thermomechanical processing on bainitic formation in several austempered Ductile Irons," Proc. 1st Conf. on Austempered Ductile Irons, Chicago, IL, 1984.

T. Shiokawa, "Austempering of nodular cast irons, their mechanical properties and some practical applications," 59th Japan Ductile Cast Iron Association Conference, 1978.

M. Johansson, "Austenitic-Bainitic Ductile Iron," Transactions, American Foundrymen's Society, 1977.

P. A. Blackmore and R. A. Harding, "The effects of metallurgical process variables on the properties of austempered ductile irons.", presented at the 1st International Conference on Austempered Ductile Iron, April 2-4, Rosemount, Chicago, Illinois, USA.

R. D. Forest, "The challenge and opportunity presented to the SG iron industry by the development of austempered Ductile Iron," BCIRA International Conference, "SG Iron-the next 40 years", 1987.

G. F. Ruff, "Comparison of Austempered Ductile Iron Versus Steel," American Foundrymen's Society Congress, Hartford, Connecticut, 1988.

S. C. Lee and C.C. Lee, "The Effects of Heat Treatment and Alloying Elements of Fracture Toughness of Bainitic Ductile Cast Iron.", AFS Transactions, vol 96, pp 827-838, 1988.

S. Shepperson and C. Allen, "The Abrasive Wear Behaviour of Austempered Spheroidal Cast Irons," International Conference on Wear of Materials, Houston, Texas, 1987.

M. Kurkinen, "Wear-resistant components in nodular cast iron.", Werkstatt und Betrieb, 1981, vol 114, No 3, pp 165-168.

H. Muhlberger, "Progress in the production, understanding, and application of Germanite-austempered Ductile Iron.", 2nd International Conference on Austempered Ductile Iron, March 17-19, 1986, Ann Arbor, Michigan, USA.

T. E. Prucha and G. F. Ruff, "Implementing Advanced Materials Through Integrated Casting Design and Manufacturing," High Integrity Castings, ASM International, 1988.

J. Janowak and R. Gundlach, "Development of a Ductile Iron for Commercial Austempering," Transactions, American Foundrymen's Society, 1983.

R. D. Forest, "Austempered Ductile Iron for Both Strength and Toughness." Machine Design, September, 1985.

M. Grech and J. M. Young, "Impact Properties of a Cu-Ni Austempered Ductile Iron," Cast Metals, 1988, vol 1 (2), 98-103.

M. Grech and J. M. Young, "Influence of Austempering Temperature on the Characteristics of Austempered Ductile Iron Alloyed with Cu and Ni.", Paper No. 90-160, presented at the American Foundrymen's Society Congress, April 20-24, 1990, Detroit Michigan, USA.

R. Christ and Cynthia Krist, et al, "Model Certification Specification-Austempered Ductile Iron (ADI)", Ductile Iron Society Department of Army Contract DAAA08-93-C-0066 (1995).

J. Keough, "An ADI Market Primer", Foundry Management & Technology, October/ November 1995.

B. Kovacs, "Development of Austempered Ductile Iron for Crankshafts", ASME 2nd International Conference on Austempered Ductile Iron, Ann Arbor, Michigan, USA, 1986.

K. Hayrynen, "Another Avenue for Ductile Iron Foundries", Modern Casting Magazine, August 1995.

J. Keough, "ADI-A Designer Gear Material", Gear Technology-The Journal of Gear Manufacturing, 1995.

R. Martinez, R. Boeri and J. Sikora, "Impact and Fracture Properties of ADI, Comparison with 4140 Steel", American Foundrymens Society Congress, 1998. Paper No. 98-008.

J. Keough, "ADI vs. Aluminum - No Contest", International Pig Iron Secretariat Competition, 1995.

B. Kovacs, J. Keough, D. Pramstaller, "Austempered Ductile Iron Process Development", Gas Research Institute Contract 5085-235-1183, (Dec. 1988).

M. Bahmani, R. Elliot and N. Varahram, "Austempered Ductile Iron: a Competitive Alternative for Forged Induction-Hardened Steel Crankshafts", International Journal of Cast Metals Research, 1997, 9,249-257.

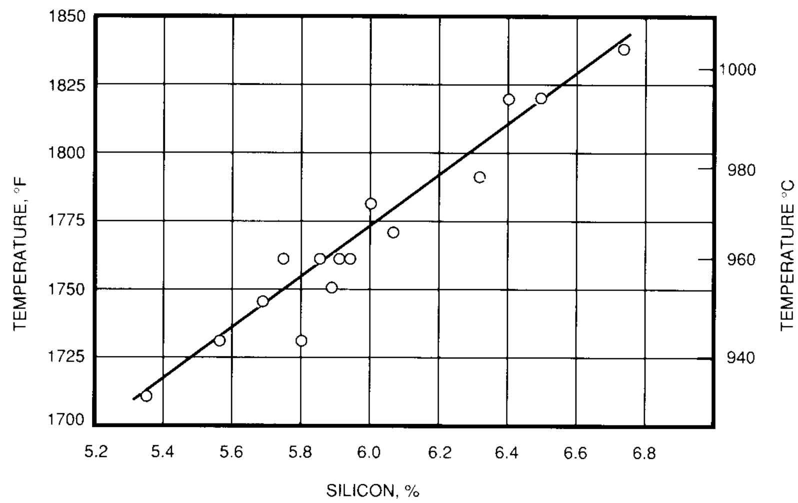
T. Chatterley, P. Murrell (MIRA/CDC), "ADI Crankshafts-An Appraisal of Their Production Potential, SAE Technical Paper Series, No. 980686. SAE Congress, Detroit, Michigan, USA, February 1998. (Reprinted from: Advancements in Fatigue Research and Applications SP-1341).

Back to Table of Contents

SECTION V

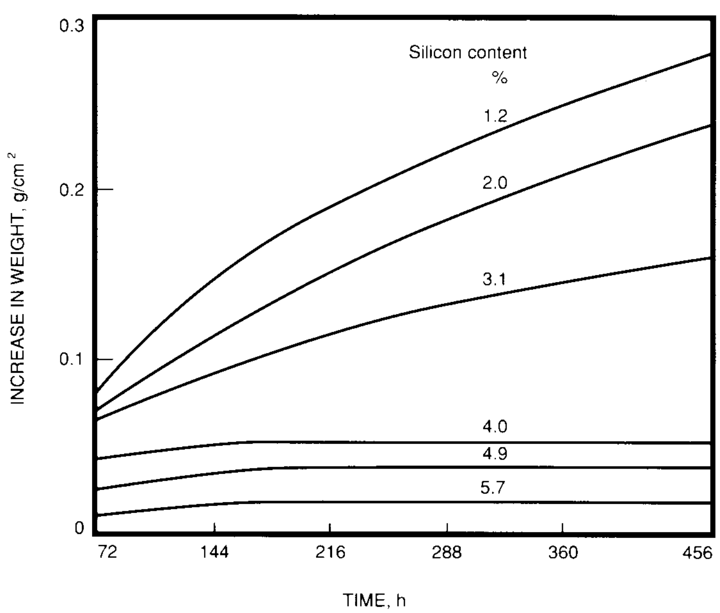
ALLOY DUCTILE IRONS

Figure 5.1



Effect of silicon content on the critical temperature in cast irons.

Figure 5.2



Effect of silicon on the oxidation of ferritic Ductile Iron in air at 650°C (1200°F).

ALLOY DUCTILE IRONS

Introduction

Three families of alloy Ductile Irons – austenitic (high nickel – Ni – Resist), bainitic and ferritic (high silicon-molybdenum) – have been developed either to provide special properties or to meet the demands of service conditions that are too severe for conventional or austempered Ductile Irons. While conventional and austempered Ductile Irons contain limited percentages of alloying elements primarily to provide the desired microstructure, alloy Ductile Irons contain substantially higher levels of alloy in order to provide improved or special properties. The high silicon levels, combined with molybdenum, give the ferritic Ductile Irons superior mechanical properties at high temperatures and improved resistance to high temperature oxidation. The high nickel content of the austenitic Ductile Irons, in conjunction with chromium in certain grades, provides improved corrosion resistance, superior mechanical properties at both elevated and low temperatures and controlled expansion, magnetic and electrical properties. Bainitic irons are used where high strength and good wear resistance are obtainable in either the as cast state or heat treated using from 1-3% alloy (Ni and Mo). The bainitic irons are not as widely used as the austenitic or Si-Mo Ductile Irons, so they will not be covered in this chapter. The reader is encouraged to contact us for more information or consult other publications such as the "Iron Castings Handbook" available through the American Foundrymen's Society.

SILICON-MOLYBDENUM DUCTILE IRONS

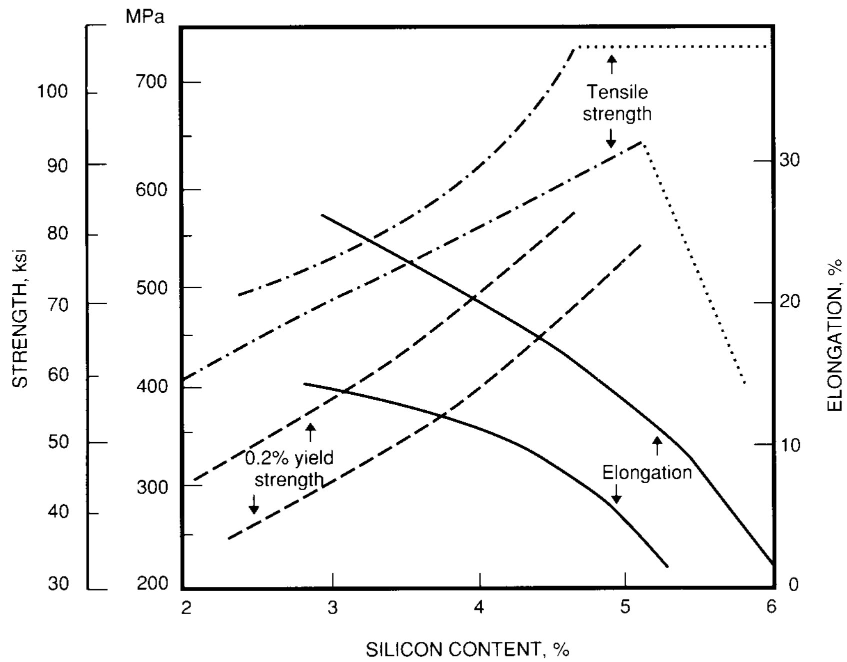
Alloy Ductile Irons containing 4-6% silicon and/or 0.4-2% molybdenum were developed to meet the increasing demands for high strength Ductile Irons capable of operating at high temperatures in applications such as exhaust manifolds or turbocharger casings. The primary properties required for such applications are oxidation resistance, structural stability, strength, and resistance to thermal cycling.

These unalloyed grades retain their strength to moderate temperatures (Figures 3.21-23), perform well under low to moderate severity thermal cycling (Figure 3.37) and exhibit resistance to growth and oxidation that is superior to that of unalloyed Gray Iron (Table 3.1). Ferritic Ductile Irons exhibit less growth at high temperatures due to the stability of the microstructure. Alloying with silicon and molybdenum significantly improves the high temperature performance of ferritic Ductile Irons while maintaining many of the production and cost advantages of conventional Ductile Irons.

Effect of Silicon

Silicon enhances the performance of Ductile Iron at elevated temperatures by stabilizing the ferritic matrix and forming a silicon-rich surface layer which inhibits oxidation. Stabilization of the ferrite phase reduces high temperature growth in two ways. First, silicon raises the critical temperature at which ferrite transforms to austenite (Figure 5.1). The critical temperature is considered to be the upper limit of the

Figure 5.3



Influence of silicon on the room temperature mechanical properties of ferritic Ductile Iron.

Table 5.1

Material	Tensile Strength ksi (MPa)			Stress Rupture ksi (MPa)
	800°F 425°C	1000°F 540°C	1200°F 650°C	1000h @ 1000°F 540°C
Gray Iron	37(255)	25(173)	12(83)	5.9(41)
60-40-18 D.I.	40(276)	25(173)	13(90)	8.3(57)
4% Si D.I.	56(386)	36(248)	13(90)	10(69)
4% Si - 1% Mo D.I.	61(421)	44(304)	19(131)	14(97)
4% Si - 2% Mo D.I.	65(449)	46(317)	20(138)	17(117)

Gray Iron: Unalloyed, stress-relieved. Ductile Irons: Sub-Critically annealed at 1450°F (788°C).

Effect of silicon and molybdenum on the high temperature tensile and creep rupture strengths of ferritic Ductile Iron.

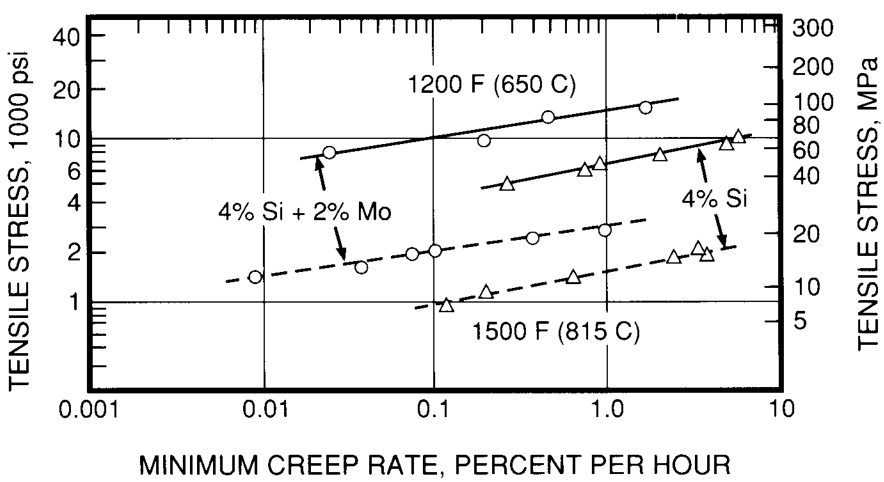
useful temperature range for ferritic Ductile Irons. Above this temperature the expansion and contraction associated with the transformation of ferrite to austenite can cause distortion of the casting and cracking of the surface oxide layer, reducing oxidation resistance. Second, the strong ferritizing tendency of silicon stabilizes the matrix against the formation of carbides and pearlite, thus reducing the growth associated with the decomposition of these phases at high temperatures.

The oxidation protection offered by silicon increases with increasing silicon content (Figure 5.2). Silicon levels above 4% are sufficient to prevent any significant weight gain after the formation of an initial oxide layer.

Silicon influences the room temperature mechanical properties of Ductile Iron through solid solution hardening of the ferrite matrix. Figure 5.3 shows that increasing the silicon content increases the yield and tensile strengths and reduces elongation. For silicon levels above 6%, the material may become too brittle for engineering applications requiring any degree of toughness. Thus, the best combination of heat resistance and mechanical properties are provided by silicon contents in the range 4-6%. The solid solution strengthening effect of silicon persists to temperatures as high as 1000°F (540°C) but above that temperature the tensile strength of high-silicon alloys is reduced as well (Table 5.1). Figures 5.4 and 5.5 illustrate the high temperature creep and stress-rupture strengths obtained in ferritic Ductile Irons containing 4% silicon.

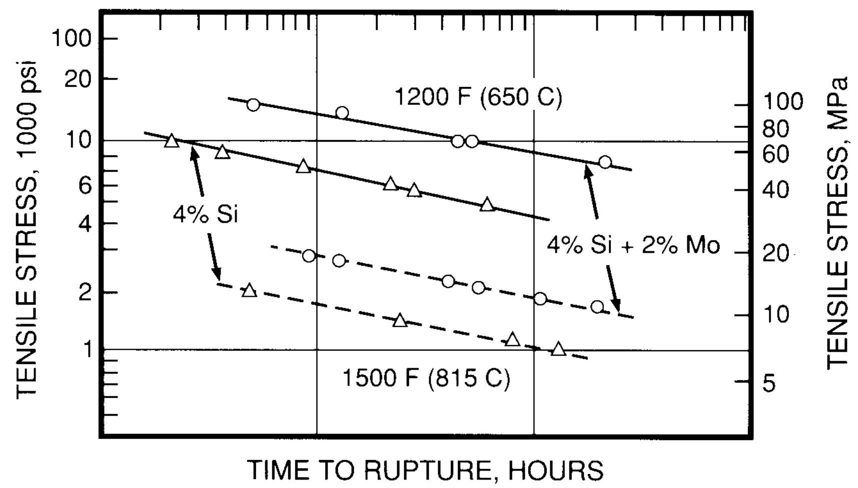
SECTION V

Figure 5.4



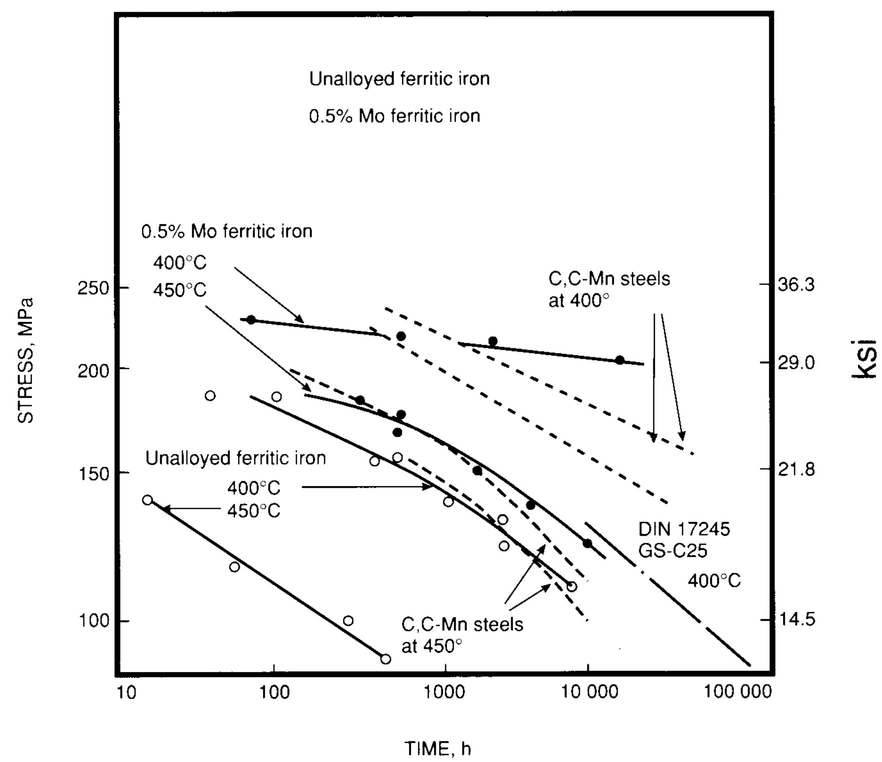
Influence of molybdenum on the minimum creep rate of ferritic Ductile Iron.

Figure 5.5



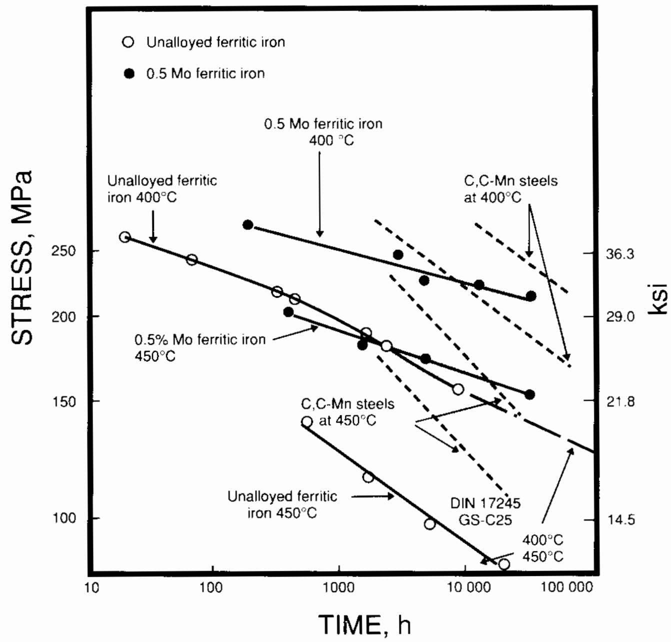
Effect of molybdenum on the stress-rupture behaviour of ferritic Ductile Iron.

Figure 5.6



1% creep strain data for ferritic Ductile Iron and C-Mn steels at 400°C (750°F) and 450°C (840°F).

Figure 5.7



Creep rupture data for ferritic Ductile Iron and C-Mn steels at 400°C (750°F) and 450°C (840°F).

Effect of Molybdenum

Molybdenum, whose beneficial effect on the creep and stress-rupture properties of steels is well known, also has a similar influence on Ductile Irons. Figures 5.6 and 5.7 show that the addition of 0.5% molybdenum to ferritic Ductile Iron produces significant increases in creep and stress rupture strengths, resulting in high temperature properties that are comparable to those of a cast steel containing 0.2% carbon and 0.6% manganese.

High Silicon with Molybdenum

The addition of up to 2% molybdenum to 4% silicon Ductile Irons produces significant increases in high temperature tensile strength (Table 5.1), stress-rupture strength (Tables 5.1 and 5.2 and Figure 5.5 and creep strength (Figure 5.4). Molybdenum additions in the range 0-1% to high-silicon Ductile Irons have been found to be very effective in increasing resistance to thermal fatigue (Table 5.3 and Figure 3.37).

Applications

High silicon-molybdenum Ductile Irons offer the designer and end user a combination of low cost, good high temperature strength, superior resistance to oxidation and growth, and good performance under thermal cycling conditions. As a result these materials have been very cost-effective in applications with service temperatures in the range 1200-1500°F (650-820°C) and where low to moderate severity thermal cycling may occur. Ductile Irons with 4% silicon and 0.6-0.8% molybdenum are presently specified for numerous automotive manifolds and turbocharger casings. High silicon irons containing 1% molybdenum are used for special high temperature exhaust manifolds and heat treating racks.

Table 5.2

Type of iron	Temperature, °C	Stress to rupture MPa (ksi) 100 h	Stress to rupture MPa (ksi) 1000 h
2.2% Si	650	40 (5.8)	20 (2.9)
4% Si	650	28 (4.1)	
4% Si 1% Mo	650	43 (6.2)	
4% Si	705	19 (2.7)	12 (1.7)
4% Si 1% Mo	705	33 (4.8)	23 (3.3)
4% Si	815	7 (1.0)	
4% Si 1% Mo	815	9 (1.3)	

Effect of silicon and molybdenum on stress-rupture strength of ferritic Ductile Irons.

Table 5.3

Type of iron	Temperature cycling, °C	Cycles to failure
2.1% Si	200 - 650	80
3.6% Si	200 - 650	173
3.6% Si 0.4% Mo	200 - 650	375
4.4% Si 0.2% Mo	200 - 650	209
4.4% Si 0.5% Mo	200 - 650	493

Influence of silicon and molybdenum on the thermal cycling behaviour of ferritic Ductile Iron.

SECTION V

Specifying Body	Spec. No.	Class or Grade	Min. Tensile psi	Min. Yield psi	% Elongation	Heat Treatment	Chemical Analysis and Hardness	% T.C.	% Si	% Mn	% P	% Ni	% Cr	BHN	Typical Applications
ASTM	A439-84	D-2	58,000	30,000	8		Min.		1.50	0.70		18.00	1.75	139	Valve stem bushings, valve and pump bodies in petroleum, salt water and caustic service, manifolds, turbocharger housings, air compressor parts.
							Max.	3.00	3.00	1.25	0.08	22.00	2.75	202	
		D-2B	58,000	30,000	7		Min.		1.50	0.70		18.00	2.75	148	Turbocharger housings, rolls.
							Max.	3.00	3.00	1.25	0.08	22.00	4.00	211	
		D2-C	58,000	28,000	20		Min.		1.00	1.80		21.00		121	Electrode guide rings, steam turbine dubbing rings.
							Max.	2.90	3.00	2.40	0.08	24.00	0.50	171	
		D-3	55,000	30,000	6		Min.		1.00			28.00	2.50	139	Turbocharger nozzles and housings, steam turbine diaphragms, gas compressor diffusers.
							Max.	2.60	2.80	1.00	0.08	32.00	3.50	202	
		D-3A	55,000	30,000	10		Min.		1.00			28.00	1.00	131	High temperature bearing rings requiring resistance to galling.
							Max.	2.60	2.80	1.00	0.08	32.00	1.50	193	
		D-4	60,000				Min.		5.00			28.00	4.50	202	Diesel engine manifolds, manifold joints.
							Max.	2.60	6.00	1.00	0.08	32.00	5.50	273	
		D-5	55,000	30,000	20		Min.		1.00			34.00		131	Guidance system housings, gas turbine shroud rings, glass rolls.
							Max.	2.40	2.80	1.00	0.08	36.00	0.10	185	
		D-5B	55,000	30,000	6		Min.		1.00			34.00	2.00	139	Optical system mirrors and parts for dimensional stability, stators for compressors.
							Max.	2.40	2.80	1.00	0.08	36.00	3.00	193	
		D-5S	65,000	30,000	10		Min.		4.90			34.00	1.75	131	Manifolds, turbine housings, turbochargers where high temperatures and severe thermal cycling occur.
							Max.	2.30	5.50	1.00	0.08	37.00	2.25	193	
ASTM ASME	A571-71 (1976) SA571	D-2M	65,000	30,000	30	Annealed	Min.	2.20	1.50	3.75		21.00		121	Compressors, expanders pumps and other pressure-containing parts requiring a stable austenitic matrix at minus 423F (−234C).
							Max.	2.70	2.50	4.50	0.08	24.00	0.20	171	

Table 5.4 **ASTM and ASME specifications and typical applications for all types of Ductile Ni-Resist Irons.**

Production Requirements

High silicon-molybdenum Ductile Irons can be produced succesfully by any competent Ductile Iron foundry that has good process control, provided that the following precautions are taken.

Carbon levels should be kept in the range 2.5-3.4%. Carbon content should be reduced as the silicon level and section size increase.

Silicon may vary from 3.7 to 6% according to the application. Increasing the silicon content improves oxidation resistance and increases strength at low to intermediate temperatures but reduces toughness and machinability.

Molybdenum contents up to 2% may be used. Increasing the molybdenum level enhances high temperature strength and improves machinability.

Pearlite and carbide stabilizing elements should be kept as low as possible to ensure a carbide-free ferritic matrix.

Normal nodularizing and inoculation practices should be used but pouring temperatures should be higher than for normal Ductile Iron. Increased dross levels require good gating and pouring practices, and increased shrinkage necessitates larger risers. Castings must be shaken out and handled carefully to avoid breakage, and all castings should be heat treated to improve toughness. Castings are commonly given a subcritical anneal – 4h at 1450°F (790°C) and furnace cooled to 400°F (200°C) – but a full anneal is required if the matrix contains significant quantities of carbides and pearlite. Machinability is similar to normal pearlitic/ferritic Ductile Irons with hardness values in the range 200-230 BHN.

AUSTENITIC DUCTILE IRONS

A family of austenitic, high alloy Ductile Irons identified by the trade name **"Ductile Ni-Resist"** have been produced for many years to meet a wide range of applications requiring special chemical, mechanical and physical properties combined with the economy and ease of production of Ductile Iron. Ductile Ni-Resist irons containing 18-36% nickel and up to 6% chromium combine tensile strengths of 55-80 ksi (380-550 MPa) and elongations of 4-40% with the following special properties:

- corrosion, erosion and wear resistance,
- good strength, ductility and oxidation resistance at high temperatures,
- toughness and low temperature stability,
- controlled thermal expansion,
- controlled magnetic and electrical properties and
- good castability and machinability.

Typical Mechanical Properties of Ductile Ni-Resist Irons

	Type D-2	Type D-2B	Type D-2C	Type D-2M*	Type D-3	Type D-3A	Type D-4	Type D-5	Type D-5B
Tensile Strength, psi	58-60000	58-70000	58-65000	65-75000	55-65000	55-65000	60-70000	55-60000	55-65000
Yield Strength, psi (.2% offset)	30-35000	30-35000	28-35000	30-35000	30-35000	30-65000	—	30-35000	30-35000
Elongation, % in 2 in.	8-20	7-15	20-40	35-45	6-15	10-20	—	20-40	6-12
Prop. Limit, psi	16.5-18500	16-19000	12-16000	—	16-19000	15-19000	12-16000	9.5-11000	10.5-13000
Mod. of Elas., psi x 10^6	16.5-18.5	16.5-19.0	15.0	17	13.5-14.5	16-18.5	13.0	16-20	16-17.5
Hardness, BHN	140-200	150-210	130-170	120-170	140-200	130-190	170-240	130-180	140-190
Impact, ft.-lb. (Charpy Vee Notch) Room Temperature	12	10	28	—	7	14	—	17	6
Compressive Yield Strength, psi (.2% offset)	35-40000	—	—	—	—	—	—	—	—
Compressive Ultimate Strength, psi	180-200000	—	—	—	—	—	—	—	—
Fatigue Limit, psi, (10^6 cycles)									
Smooth bar	30000	—	—	—	—	—	—	—	—
Notched Bar	20000	—	—	—	—	—	—	—	—

* Normalized from 1700 F.

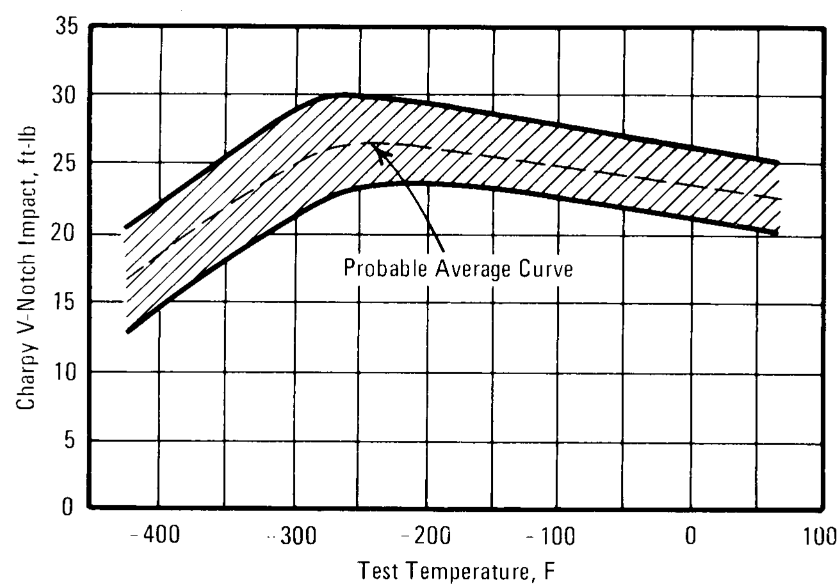
Table 5.5 **Typical room temperature mechanical properties of Ductile Ni-Resist Irons.**

Sub-Zero Temperature Impact Properties
Charpy Vee Notch (ft-lb)

	Type D-2	Type D-2C	Type D-3	Type D-3A	Type D-5	Type D-5B
Room Temperature	12.5	28	7	14	17	5.5
0 F	11.5	15	—	14	15	5.5
−100 F	10	6.5	6.5	13	14	4.5
−320 F	4.5	4	3.5	7.5	11	4

Table 5.6 **Effect of temperature on impact properties of different types of Ductile Ni-Resist (1ft-lbf = 1.3558 J).**

Figure 5.8



Effect of temperature on the impact properties of type D-2M Ductile Ni-Resist (1ft-lbf = 1.3558 J).

Specifications and Recommendations

Table 5.4 summarizes the ASTM and ASME specifications for Ductile Ni-Resist Irons and lists typical applications for each grade. Section XII contains further information on international specifications for these materials. The applications listed for each grade take advantage of the following general characteristics.

Type D-2, the most commonly used grade, is recommended for service requiring resistance to corrosion, erosion and frictional wear up to temperatures of 1400°F (760°C).

Type D-2B provides higher resistance to erosion and oxidation than Type D-2 and is also recommended for use with neutral and reducing salts.

Type D-2C is recommended where resistance to corrosion is less severe and high ductility is required.

Type D-2M (2 classes) is recommended for cryogenic applications requiring structural stability and toughness.

Type D-3 exhibits excellent elevated temperature properties and resistance to erosion. It is recommended for applications involving thermal shock and thermal expansion properties similar to ferritic stainless steels.

Type D-3A provides good resistance to galling and wear, and intermediate thermal expansion.

Type D-4 provides resistance to corrosion, erosion and oxidation that is superior to Types D-2 and D-3.

Type D-5 is recommended for applications requiring minimum thermal expansion.

Type D-5B should be used in applications requiring minimum thermal stresses, and good mechanical properties and resistance to oxidation at high temperatures.

Type D-5S provides excellent resistance to oxidation when exposed to air at temperatures up to 1800°F (980°C) and is also recommended for applications involving thermal cycling at temperatures up to 1600°F (870°C).

Mechanical Properties

The room temperature mechanical properties of Ductile Ni-Resist Irons are described in Tables 5.4 and 5.5. The data shown in Table 5.5 are from either 1 inch (25 mm) keel blocks or castings tested in the as-cast condition. Castings should be ordered according to ASTM A439 or other specifications, but for special applications specific properties may be defined in more detail by agreement between the customer and the foundry.

Elevated Temperature Properties of Ductile Ni-Resist Alloys

	Type D-2	Type D-2 with Mo	Type D-2C	Type D-3	Type D-3 with Mo	Type D-4	Type D-4 with Mo	Type D-5B	Type D-5B with Mo
Tensile Strength, psi									
Room Temp.	59400	61500	62200	58300	61000	64000	60500	60800	61200
800 F	54000	—	52400		—	—		—	
1000 F	47700	37000	42000	48000	46800	60700	54500	47200	48800
1200 F	35600	38500	28000	41700	44000	48000	45500	40600	46400
1400 F	22100	24900	17200	26500	28800	21800	22300	24900	31100
Yield Strength, psi									
Room Temp.	35000	37500	34100	39300	40000	44300	43000	41000	41000
800 F	28000	—	26200	—		—	—		
1000 F	28000	29200	23100	28400	28500	41400	38400	25800	28600
1200 F	25000	25200	24200	27400	29000	34000	35500	24200	29900
1400 F	17000	17100	16600	15200	21800	18500	18600	18600	24300
Impact Strength (unnotched Charpy, ft lbs.)									
Room Temp.	26	23*	—	—	—	—	—		—
1000 F	35	21*	—	—	—	—		—	—
1100 F	29	23*	—	—	—	—		—	—
1200 F	32	24*	—	—		—	—	—	
1350 F	42	27*	—	—	—	—	—	—	—
1500 F	35	27*	—	—	—	—		—	—
Stress Rupture (1000 hrs)									
1000 F	28000	—	21000	—	—	—		—	—
1100 F	(18000)	26000	(13500)	23500	30500	17000	19000	25000	32000
1200 F	12000	(15500)	9000	(15000)	(18000)	(9500)	(11000)	(15000)	(18500)
1300 F	(8500)	11000	(6000)	9700	11000	6200	7500	10000	12000
1400 F	(5500)	(6000)	(4000)	(6000)	(7000)	(3000)	(4000)	(5500)	(6500)
Creep Data (0.0001%/hr)									
1000 F	23000	(27000)	13000	—	(29000)	—		(27000)	(28000)
1100 F	(13100)	16000	(9000)	—	18000			(16000)	17000
1200 F	8000	(9600)	5700	—	(12000)			(9600)	(10500)
1300 F	(4800)	5600	(3400)	—	7000			8000	(6000)
(0.00001%/hr)									
1000 F	9000	(18000)	—	—	(21000)	—		—	(18000)
1100 F	(5600)	11000	—	—	13000			10000	11000
1200 F	3400	(6000)	—	—	(8000)		—	—	(6700)
1300 F	(2100)	3600	—	—	5000		—	5600	4000
Elongation (%)									
Stress Rupture									
1000 F	6	—	14	—		—		—	
1100 F	—	5.5	—	7	5	10.5	10	6.5	5.5
1200 F	13	—	13		—		—	—	—
1300 F	—	11.5	—	12.5	16	25	21	13.5	11.5
Short Time Tensile									
Room Temp.	10.5	8.5	25	7.5	7	3.5	2.5	7	7.5
800 F	12	—	23	—	—	—	—	—	—
1000 F	10.5	1.5	19	7.5	7	4	3.5	9	7.5
1200 F	10.5	3	10	7	4	11	8	6.5	6.5
1400 F	15	14.5	13	18	13	30	24.5	24.5	12.5

Footnote: Values in parentheses are extrapolated or interpolated. * Type D-2B no Mo.

Table 5.7 **Elevated temperature properties of Ductile Ni-Resist Irons.**

Elastic Properties

Ductile Ni-Resist Irons have elastic moduli in the range 13-19 × 10^6 psi (90-130 GPa). These values are significantly lower than those of conventional Ductile Irons and are very similar to Ni-Resist irons with flake graphite. The proportional limit of as-cast Ductile Ni-Resists varies from 10 to 19 ksi (70-130 MPa), reflecting the influence of the austenite matrix and chromium content on initial yielding.

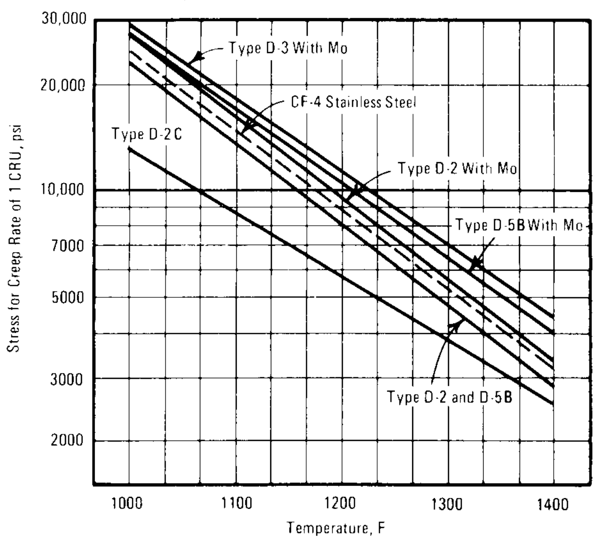
Strength and Elongation

With the exception of Type D-2M, the 0.2% yield strength and tensile strength are similar for all Types because of their common austenitic matrix. Unlike strength, elongation and toughness vary significantly between Types, depending upon the chromium, molybdenum, and silicon contents. In the low-chromium Types D-2C and D-5, as-cast elongations vary from 25 to 40%, with correspondingly good toughness. Types D-2, D-2B, D-3 and D-5B, all containing nominally 2 to 3% chromium, have as-cast elongations the range of 5 to 20% and lower toughness. Due to the stability of the austenite matrix, the mechanical properties of Ductile Ni-Resists are not strongly affected by heat treatments. High temperature treatments to disperse carbides can increase the yield and tensile strengths of Type D-2 by 10-15 ksi (70-105 MPa) while retaining good elongation. Annealing treatments may improve elongation values through the reduction of the carbide content and the spheroidization of any remaining carbides.

Low Temperature Properties

Ductile Ni-Resist Irons, due to their austenitic matrices, retain their toughness and ductility to very low temperatures (Table 5.6). Type D-2M, with slightly higher nickel and manganese contents to extend the stability of the austenite phase to extremely low temperatures, improves on the already superior low temperature properties demonstrated by the other Types of Ni-Resist. Figure 5.8 shows that the Charpy v-notch impact energy of Type D-2M increases with decreasing temperature, peaking at − 275°F (− 170°C) and retaining room temperature toughness to temperatures as low as − 320°F (− 195°C).

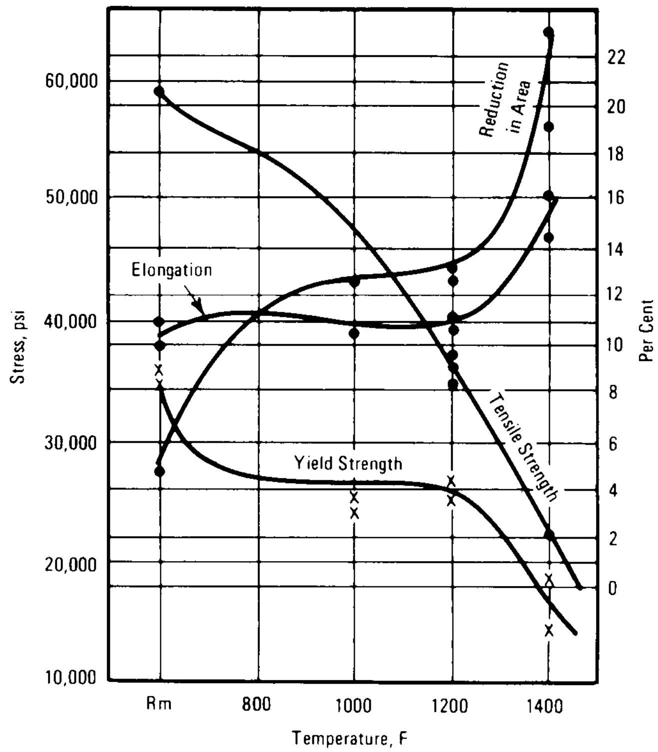
Figure 5.9



Comparison of creep strengths of several Ductile Ni-Resist Irons and CF-4 stainless steel.

SECTION V

Figure 5.10



Short-term tensile properties of type D-2 Ductile Ni-Resist at elevated temperatures.

Table 5.8

Oxidation Resistance		
	Inches Penetration Per Year	
	Test 1	Test 2
Ductile Iron (2.5 Si)	.042	.50
Ductile Iron (5.5 Si)	.004	.051
Ductile Ni-Resist Type D-2	.042	.175
Ductile Ni-Resist Type D-2C	.07	—
Ductile Ni-Resist Type D-4	.004	0.0
Conventional Ni-Resist Type 2	.098	.30
Type 309 Stainless Steel	0.0	0.0

Test 1—Furnace atmosphere—air, 4000 hr. at 1300 F.
Test 2—Furnace atmosphere—air, 600 hr. at 1600-1700 F, 600 hr. between 1600-1700 F, and 800-900 F, 600 hr. at 800-900 F.

Oxidation resistance of Ductile Ni-Resists, Ni-Resist, conventional and high silicon Ductile Irons and type 309 stainless steel.

SECTION V

High Temperature Properties

Table 5.7 summarizes the high temperature mechanical properties of the various Types of Ductile Ni-Resist Irons. Creep data for these materials are shown in Figure 5.9, with those of CF-4 stainless steel included for reference. The addition of 1% molybdenum to Ductile Ni-Resist increases the high temperature creep and rupture strengths of Types D-2, D-3 and D-5B to the extent that their creep and rupture properties are equal or superior to those of cast stainless steels HF and CF-4. Figure 5.10 shows the short-term, tensile properties of Type D-2 from room temperature to 1400°F (760°C). It is interesting to note that there is no temperature range in which embrittlement occurs, and that yield strength does not decrease appreciably until temperatures exceed 1200°F (650°C).

Thermal Cycling Resistance

When cycled to temperatures of 1250°F (675°C) and above, conventional ferritic Ductile Irons and steels pass through a "critical range" in which phase changes produce volume changes resulting in warping, cracking and loss of oxidation resistance. Ductile Ni-Resist Irons, because they are austenitic at all temperatures, do not undergo such phase changes and thus possess superior resistance to high temperature thermal cycling.

Oxidation Resistance

Table 5.8 compares oxidation data for certain Types of Ductile Ni-Resist with conventional and high-silicon Ductile Irons, conventional Ni-Resist, and type 309 stainless steel. The chromium-containing Ductile Ni-Resists D-2, D-2B, D-3, D-4 and D-5B provide good resistance to oxidation and maintain satisfactory mechanical properties at temperatures as high as 1400°F (760°C). These properties make these grades highly suitable for applications such as furnace parts, exhaust lines and valve guides. For service temperatures exceeding 1300°F (700°C), Types D-2B, D-3, and D-4 are preferable. Type D-5S, with its superior dimensional stability and oxidation resistance, should be used when these properties are required for service temperatures as high as 1600°F (870°C).

Corrosion Resistance

Ductile Ni-Resists and Ni-Resist with flake-type graphite exhibit corrosion resistance which is intermediate between those of unalloyed Ductile Iron and chromium-nickel stainless steels. Table 5.9 summarizes the corrosion resistance of Types D-2 and D-2C Ductile Ni-Resist in a number of corrosive environments. It is generally desirable to have chromium contents in excess of 2% for materials exposed to corrosive media. Therefore, Types D-2, D-2B, D-3, D-4, D-5B and D-5S are recommended for applications where a high level of corrosion resistance is desired. There are exceptions to these general comments and the reader is advised to consult the International Nickel Company bulletin "Engineering Properties and Applications of Ni-Resists and Ductile Ni-Resists." for information on the corrosion behaviour of Ductile Ni-Resist Irons in over 400 environments.

Wear and Galling

The presence of dispersed graphite, as well as the work-hardening character of Ductile Ni-Resist alloys, provide a high level of resistance to frictional wear and galling. Types D-2, D-2C, D-3A and D-4 offer good

Corrosion Resistance of Ni-Resist Austenitic Nickel Irons

Expressed in inches penetration per year (i.p.y.)

Corrosive Media	Type D-2C	Type D-2
Ammonium chloride solution: 10% NH_4Cl, pH 5.15, 13 days at 30 C (86 F), 6.25 ft/min.	0.0280	0.0168
Ammonium sulfate solution: 10% $(NH_4)_2SO_4$, pH 5.7, 15 days at 30 C (86 F), 6.25 ft/min.	0.0128	0.0111
Ethylene vapors & splash: 38% ethylene glycol, 50% diethylene glycol, 4.5% H_2O, 4% Na_2SO_4, 2.7% NaCl, 0.8% Na_2CO_3 + trace NaOH, pH 8 to 9, 85 days at 275-300 F	0.0023	0.0019*
Fertilizer: commercial "5-10-5", damp, 290 days at atmospheric temp.	—	0.0012
Nickel chloride solution: 15% $NiCl_2$, pH 5.3, 7 days at 30 C (86 F), 6.25 ft/min.	0.0062	0.0040
Phosphoric acid, 85%, aerated at 30 C (86 F), Velocity 16 ft. per min., 12 days	0.213	0.235
Raw sodium chloride brine, 300 gpl of chlorides, 2.7 gpl CaO, 0.06 gpl NaOH, traces of NH_3 & H_2S, ph 6-6.5, 61 days at 50 F, .1 to .2 fps	0.0023	0.0020*
Sea water at 26.6 C (80 F), Velocity 27 ft per sec, 60 day test	0.039	0.018
Soda & brine: 15.5% NaCl, 9.0% NaOH, 1.0% Na_2SO_4, 32 days at 180 F	0.0028	0.0015
Sodium bisulfate solution: 10% $NaHSO_4$, pH 1.3, 13 days at 30 C (86 F), 6.25 ft/min.	0.0431	0.0444
Sodium chloride solution: 5% NaCl, pH 5.6, 7 days at 30 C (86 F), 6.25 ft/min.	0.0028	0.0019
Sodium hydroxide: 50% NaOH + heavy conc. of suspended NaCl, 173 days at 55 C (131 F), 40 gal/min.	0.0002	0.0002
" 50% NaOH saturated with salt, 67 days at 95 C (203 F), 40 gal/min.	0.0009	0.0006
" 50% NaOH, 10 days at 260 F, 4 days at 70 F	0.0048	0.0049
" 30% NaOH + heavy conc. of suspended NaCl, 82 days at 85 C (185 F)	0.0004	0.0005
" 74% NaOH, 19¾ days, at 260 F	0.005	0.0056
Sodium sulfate solution: 10% Na_2SO_4, pH 4.0, 7 days at 30 C (86 F), 6.25 ft/min.	0.0136	0.0130
Sulfuric acid: 5%, at 30 C (86 F) aerated, Velocity 14 ft per min., 4 days	0.120	0.104
Synthesis of sodium bicarbonate by Solvay process: 44% solid $NaHCO_3$ slurry plus 200 gpl NH_4Cl, 100 gpl NH_4HCO_3, 80 gpl NaCl, 8 gpl $NaHCO_3$, 40 gpl CO_2, 64 days at 30 C (86 F)	0.0009	0.0003
Tap water aerated at 30 F, Velocity 16 ft per min., 28 days	0.0015	0.0023
Vapor above ammonia liquor: 40% NH_3, 9% CO_2, 51% H_2O, 109 days at 85 C (185 F), low velocity	0.011	0.025
Zinc chloride solution: 20% $ZnCl_2$, pH 5.25, 13 days at 30 C (86 F), 6.25 ft/min.	0.0125	0.0064

* Contains 1% chromium.

Table 5.9 **Corrosion resistance of Ductile Ni-Resist Irons. Types D-2 and D-2C.**

SECTION V

Physical Properties of Ductile Ni-Resist

	Type D-2	Type D-2B	Type D-2C	Type D-3	Type D-3A	Type D-4	Type D-5	Type D-5B
Specific Gravity	7.41	7.45	7.41	7.45	7.45	7.45	7.68	7.72
Density, lb. per cu. in.	.268	.27	.268	.27	.27*	.27	.278	.279
Melting Point, F.	2250	2300	2250	2250	2250	2200	2250	2250
Thermal Expansion 70-400 F., Millionths per °F.	10.4	10.4	10.2	7.0		8.0		
Thermal Conductivity, Cal./cc/sec/°C.	.032	–	–	—				
Electrical Resistivity, microhms per cc	102			—				
Magnetic Response	Non-magnetic	Slightly magnetic	Non-magnetic	Definitely magnetic	Definitely magnetic	Slightly magnetic	Definitely magnetic	Definitely magnetic
Magnetic Permeability, H = 300 at room temp.	1.02-1.04	1.04-1.08	1.03			1.10		

Table 5.10 **Physical properties of Ductile Ni-Resist.**

wear properties when used with a wide variety of other metals at temperatures from sub-zero to 1500°F (815°C). Tests performed from room temperature to 1000°F (540°C) have shown that Types D-2 and D-2C have lower wear rates than bronze, unalloyed Ductile Iron, and **INCONEL 600**. The improved wear resistance is attributed to the spheroidal graphite and the formation of a nickel oxide film at higher temperatures. Types D-2B and D-3 provide inferior wear resistance compared to other Ductile Ni-Resists because they contain massive carbides which might abrade a mating material.

Erosion Resistance

Ductile Ni-Resist castings, particularly those containing higher chromium levels, provide excellent service where resistance to erosion and corrosion are required, such as in the handling of wet steam, salt slurries and relatively high velocity corrosive liquids. Steam turbine components such as diaphragms, shaft seals and control valves are proven examples of the excellent resistance of Types D-2 and D-3 to steam erosion at high temperatures. Resistance to cavitation erosion makes Ductile Ni-Resist suitable for pump impellers and small-boat propellers. Higher-chromium Types D-2B, D-3, and D-4 are recommended when cavitation erosion is severe. Service results show that Type D-2 is superior to straight chromium stainless steels or bronzes in resisting cavitation for applications such as boat propellers and pump impellers.

Physical Properties

Table 5.10 summarizes the general physical properties of Ductile Ni-Resist Irons.

Thermal Conductivity

The thermal conductivities of Type D-2 Ductile Ni-Resist, Ni-Resist, Gray Iron and several steels are listed in Table 5.11. The spheroidal graphite shape and austenitic matrix are responsible for the relatively low conductivity of Ductile Ni-Resists.

Thermal Expansion

Figures 5.11 and 5.12 illustrate the wide range of thermal expansion exhibited by the different Types of Ductile Ni-Resist and the influence of nickel content on the thermal expansion behaviour of Type D-3. High expansion Types D-2 and D-4 are used to match the expansion of materials such as aluminium, copper, bronze and austenitic stainless steels. Type D-3, with different nickel levels, is used to obtain the controlled, intermediate thermal expansion required to match the thermal expansions of a wide variety of steels and cast irons. Types D-5 and D-5B are recommended for applications requiring maximum dimensional stability, such as machine tool parts, glass molds and gas turbine housings.

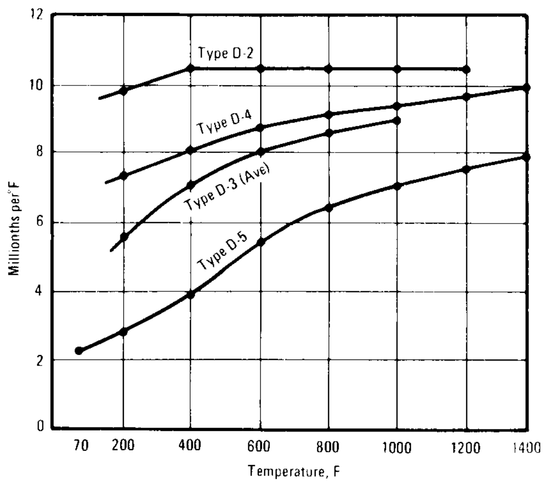
Electrical and Magnetic Properties

Table 5.12 compares the electrical resistivity of Type D-2 Ductile Ni-Resist with that of Ni-Resist, Gray Iron and various steels. Table 5.13 compares the magnetic permeability of all Types of non-magnetic Ductile Ni-Resist with that of Ni-Resist, Gray Iron, bronzes and a variety of steels. Values for Types D-3, D-3A, D-5 and D-5B are not shown because they are ferromagnetic. The non-magnetic character of Types D-2 and

Thermal Conductivity		
Material	Cal/cm³/sec/°C (0 to 100 C)	Btu/Hr/Ft²/in/°F (50-200 F)
Ductile Ni-Resist Type D-2	0.032	93
Flake Graphite Ni-Resist	0.090-0.095	260-275
Gray Cast Iron	0.108-0.131	313-380
Steel	0.15 -0.17	435-495
12% Cr Steel	0.045	130
18% Cr -8% Ni Steel	0.039	113

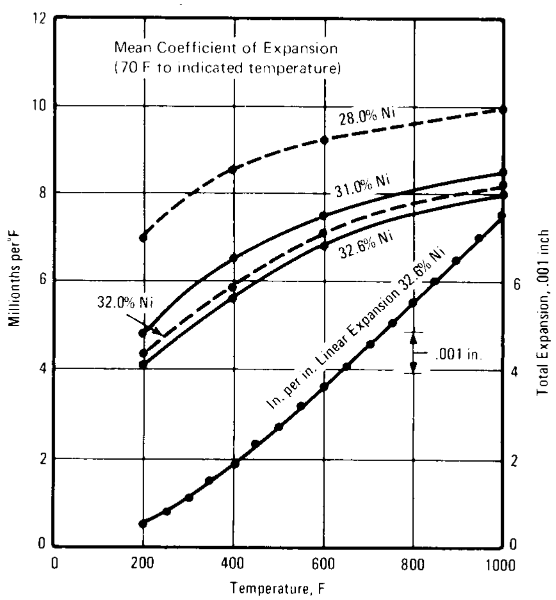
Table 5.11 **Thermal conductivity of type D-2 Ductile Ni-Resist, Ni-Resist, Gray Iron, and steels.**

Figure 5.11



Mean coefficient of thermal expansion for various types of Ductile Ni-Resist.

Figure 5.12



Effect of nickel on the thermal expansion of type D-3 Ductile Ni-Resist.

SECTION V

D-2C has been applied in several industrial applications where magnetic permeability must be kept at a minimum in order to prevent excessive heat generation and power loses from eddy currents.

Production Requirements

Special Ductile Iron foundry practices, some of which affect casting design, are required for the production of Ductile Ni-Resist castings. To obtain maximum casting performance and minimum production cost, the design engineer should initiate consultations, at an early stage in the design process, with a Ductile Iron foundry experienced in the production of Ductile Ni-Resist castings.

Machinability

The machinability of Ductile Ni-Resists falls between that of pearlitic Gray Iron with a hardness of about 240 BHN and mild steel when machining practices follow those recommended in the Inco publication A242, "Machining and Grinding Ni-Resist and Ductile Ni-Resist."

Heat Treatment

Large and complex Ductile Ni-Resist castings should be mold-cooled to 600°F (315°C) before shakeout to relieve stresses. When required, stress-relief should be performed at 1150-1250°F (620-675°C). Annealing, which softens and improves ductility primarily by the decomposition and spheroidization of carbides, should be conducted at 1750-1900°F (960-1035°C) for 1 to 5 hours, depending on section size and the degree of decomposition and spheroidization desired. Annealing should be followed by air cooling or furnace cooling if minimum hardness and maximum elongation are required.

When Ductile Ni-Resist is to be used at temperatures of 900°F (480°C) and above, the casting can be stabilized to minimize growth and warpage by holding at 1600°F (870°C) for two hours, followed by furnace cooling to 1000°F (540°C), followed by air cooling to room temperature. To assure dimensional stability for all Types of Ductile Ni-Resist, the following heat treatment should be performed: hold at 1600°F (870°C) for 2 hours plus 1 hour per inch of section size; furnace cool to 1000°F (540°C); hold for 1 hour per inch of section size, and slowly cool to room temperature. After rough machining, reheat to 850-900°F (450-480°C) and hold for 1 hour per inch of section size to relieve machining stresses. Furnace cool to below 500°F (260°C).

SECTION V

Table 5.12

Electrical Resistance

Material	Electrical Resistance (microhms/cc)
Ductile Ni-Resist Type D-2	102
Flake Graphite Ni-Resist	130-170
Gray Cast Iron	75-100
Plain Medium C Steel	18
12% Cr Steel	57
18% Cr-8% Ni Steel	70

Electrical resistivity of Ductile Ni-Resist, Ni-Resist, Gray Iron and different steels.

Table 5.13

Magnetic Permeability

Material	Permeability
Ductile Ni-Resist Type D-2	1.02-1.04
Ductile Ni-Resist Type D-2B	1.04-1.08
Ductile Ni-Resist Type D-2C	1.03
Ductile Ni-Resist Type D-2M	1.01-1.03
Ductile Ni-Resist Type D-4	1.10
Flake Graphite Ni-Resist	1.03
Gray Cast Iron*	125
Mild Steel*	150
12% Cr Steel	Ferromagnetic
10-14% Mn Steel	1.03-1.10
18% Cr-8% Ni Steel	<1.001
Bronzes	<1.001

* Initial permeability.

Magnetic permeability of different types of Ductile Ni-Resist, Ni-Resist, Gray Iron, various steels and bronzes.

REFERENCES

S. I. Karsay, Ductile Iron II, Quebec Iron and Titanium Corporation, 1972.

Annual Book of ASTM Standards, Volume 01.02, Ferrous Castings, 1987.

Engineering Properties and Applications of the Ni-Resists and Ductile Ni-Resists, The International Company, New York, NY, 1978.

The Iron Castings Handbook, Iron Castings Society, Inc., 1981.

Metals Handbook, American Society for Metals, Vol. 1, 8th edition, 1961.

E. Soehnchen and O. Bernhofen, "The Thermal Expansion Coefficient of Cast Iron," Archive fur das Eisenhattenwesen, Vol. 8, 1935.

H. T. Angus, Cast Iron: Physical and Engineering Properties, 2nd ed., Butterworths Inc, 1967.

E. Piwowarsky, Hochwertiges Gusseisen, Springer-Verlag, Berlin, 1942.

G. N. J. Gilbert, Engineering Data on Nodular Cast Irons, British Cast Iron Research Association, 1968.

High Strength Irons, Climax Molybdenum Company, New York.

Ductile Iron, International Nickel Company, New York, NY, 1956.

"Ductile Iron" Alloy Digest Data Sheet, Engineering Alloys Digest, Inc., Upper Montclair, NJ, 1956.

"Ductalloy," Alloy Digest Data Sheet, Engineering Alloys Digest, Inc., Upper Montclair, NJ, 1956.

B. E. Neimark, et al, "Thermophysical Properties of Cast Irons," Russian Castings Production, September, 1967.

A Design Engineer's Digest of Ductile Iron, 5th edition, 1983, QIT-Fer et Titane Inc., Montreal, Quebec, Canada.

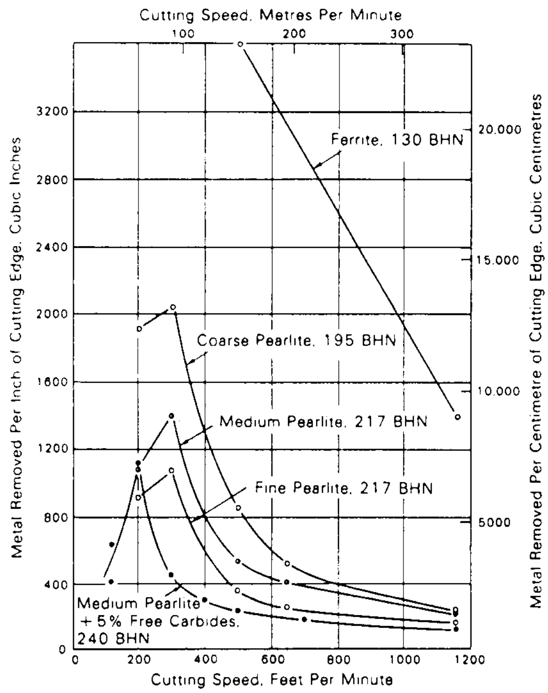
Ductile Iron, Metals Handbook, American Society for Metals, 9th edition, Vol 15, 1988.

W. Fairhurst and K. Röhrig "High-silicon Nodular Irons." Foundry Trade Journal, March 29, 1979, pp. 657-681.

SECTION VI

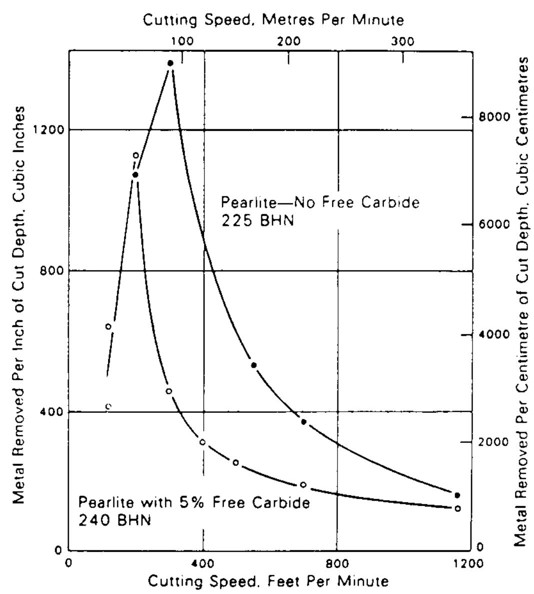
MACHINABILITY

Figure 6.1



Relationship between tool life and matrix microstructure.

Figure 6.2



Effect of free carbides on tool life.

SECTION VI

MACHINABILITY

Introduction

In order to succeed in the fiercely competitive international markets for all finished products, from motorcycles to machine tools, manufacturers must offer the end user the best value – the highest ratio of quality to cost. In order to maximize quality while minimizing cost, designers have added manufacturability to the list of criteria that must be met by a successful design. This trend toward increasing importance of manufacturability has been confirmed by the results of a survey of 2500 design engineers conducted by the Ductile Iron Group. When asked to rank 19 materials selection criteria in order of importance, respondents placed both ease of machining and cost of manufacture in the top six. In modern manufacturing terminology, manufacturability is an attribute which indicates how economically a component can be machined to meet customer specifications. This concept embraces the traditional indicators of machinability – tool life, power requirements, and surface finish and accuracy – and adds other manufacturability criteria such as cycle times, yield, scrap, consistency, inventory requirements, compatibility with automated NC machining, and overall manufacturing cost.

The production of most finished metal products involves machining operations to produce the desired final shape. Castings offer the designer the lowest cost route for the production of complex shapes because they can be cast to near final shape, reducing both machining and materials costs. Near net shape casting technology and improved dimensional consistency offered by competent, modern foundries yield additional savings in manufacturing costs. Ductile Iron, with its excellent castability, offers the designer all the manufacturing advantages of castings plus the added benefits of a machinability: strength ratio that is superior to other cast irons and cast steels.

Machinability

Machinability is not an intrinsic property of a material, but rather the result of complex interactions between the workpiece and various cutting devices operated at different rates under different lubricating conditions. As a result, machinability is measured empirically, with results applicable only under similar conditions. Traditionally, machinability has been measured by determining the relationship between cutting speed and tool life because these factors directly influence machine tool productivity and machining costs. The increased use of disposable inserts has reduced tool life costs and this factor, along with a greater emphasis on quality, has increased the importance of surface finish and dimensional accuracy and consistency.

Effect of Microstructure

Machinability is determined by microstructure and hardness. The graphite particles in Gray, Malleable and Ductile Irons are responsible for the free-machining characteristics of these materials and their superior machinability when compared to steels. Within the cast irons, graphite morphology plays an important role in machinability, with the graphite

Table 6.1

Machining operation	Tool-life improvement %
Pinion blanking	
– centre press	30
– drill	35
– rough lathes	70
– finish lathes	50
– grind	20
Rear-gear blanking	
– bullard turning	200
– drilling	20
– reaming	20
Gleason machining	
– pinion – roughing	900
– finishing	233
– ring – roughing	962
– finishing	100

Tool life improvement resulting from the replacement of forged steel gear blanks by ferritic Ductile Iron.

Component	Operation	Ductile Iron		Steel	
		No. machined	Wear, mm	No. machined	Wear, mm
Crown wheel	Rough boring	250 – 300	0.5 – 0.7	80 – 100	1.5
	Facing	250	0.2	100	0.4
	Drilling, reaming and tapping of bolt holes	1300	–	500	–
	Rough tooth-cutting	1300	0.4 – 0.5	180	0.9 – 1.0
	Finish tooth-cutting	1300	0.2	200	0.5
Bevel pinion	Hoading of both ends	3200	–	1600	–
	Turning of shank and conical head	400	0.4	200	–
	Rough tooth-cutting	1300	0.4 – 0.5	200	0.9 – 1.0
	Finish tooth-cutting	1300	0.2	200	0.4

Table 6.2 **Comparison of the machinability of a ferritic Ductile Iron and a forged 18CrMo4 steel.**

flakes found in Gray Iron providing superior machining characteristics. While the graphite particles influence cutting force and surface finish, the matrix is the primary determinant of tool life.

Hardness is often used as an indicator of machinability because of the close relationship between hardness and microstructure. However, hardness gives an accurate representation of machinability only for similar microstructures. For example, a tempered martensite matrix will exhibit superior machinability to a pearlitic matrix of similar hardness. Figure 6.1 describes the relative machinability of the following common matrix components in Ductile Iron.

Ferrite is the softest matrix constituent in Ductile Iron and as a result exhibits the best machinability. While not as soft as the ferrite in steel, the ferrite in Ductile Iron gives superior machinability due to the effect of silicon, which decreases ferrite toughness, and the lubricating and chip-breaking effects of the graphite spheroids. Machinability increases with silicon content up to about 3% but decreases significantly with increasing silicon content above this level.

Pearlite, which consists of an intimate mixture of soft ferrite and hard lamellar iron carbide, is a common matrix component in all intermediate strength grades of Ductile Iron. The volume fraction of pearlite and the fineness of the lamellae determine the hardness and the machinability of Ductile Iron. Although machinability decreases with increasing pearlite content, pearlitic irons are considered to have the best combination of machinability and wear resistance. Figure 6.1 shows that pearlite fineness affects machinability and that the effect of hardness decreases as pearlite fineness increases.

Carbides are the hardest constituents in Ductile Iron and have the poorest machinability. When present as thin lamellae in pearlite they are easily sheared and are in their most machinable form. When present as massive or "free" carbide, both iron and alloy carbides cause a dramatic reduction in machinability (Figure 6.2).

Martensite is an extremely hard matrix phase produced by quenching Ductile Iron. It is too hard and brittle to be machined as quenched, but tempering martensite is more machinable than pearlite of similar hardness.

Other structures such as acicular bainite and ferrite are produced by interrupted cooling in Ductile Irons with sufficient hardenability to suppress the formation of ferrite and pearlite. Acicular microstructures have a similar machinability to martensite tempered to the same hardness.

Comparative Machinability

Improved machinability is often one of the benefits gained when a steel component is replaced by a Ductile Iron casting. Machining Handbooks

Machining Operation	60-40-18 152 BHN Microinch	60-40-18 152 BHN µm	80-55-06 223 BHN Microinch	80-55-06 223 BHN µm	100-70-03 265 BHN Microinch	100-70-03 265 BHN µm	120-90-02 302 BHN Microinch	120-90-02 302 BHN µm
Turning, Carbide, Roughing Depth with soluble oil	60-80	*1.52-2.03*	55-80	*1.40-2.03*	60-100	*1.52-2.5?*	60-100	*1.52-2.54*
Turning, Carbide, Finishing Depth with soluble oil	70-80	*1.78-2.03*	40-60	*1.02-1.52*	50-100	*1.27-2.54*	50-100	*1.27-2.54*
Face Milling, Carbide, Roughing Depth with and without face land	100-400	*2.54-10.16*	70-350	*1.78-8.89*	70-400	*1.78-10.16*	90-400	*2.29-10.16*
Face Milling, Carbide, Finishing Depth with face land	80-120	*2.03-3.05*	60-80	*1.52-2.03*	60-70	*1.52-1.78*	80-110	*2.03-2.79*
Surface Grinding, Roughing	15-30	*0.38-0.76*	15-25	*0.38-0.64*	15-25	*0.38-0.64*	15-25	*0.38-0.64*
Surface Grinding, Finishing	4-15	*0.10-0.38*	4-15	*0.10-0.38*	3-12	*0.08-0.30*	3-10	*0.08-0.25*
Cylindrical Grinding, Roughing*	21	*0.53*	21	*0.53*	21	*0.53*	21	*0.53*
Cylindrical Grinding, Finishing*	4	*0.10*	4	*0.10*	4	*0.10*	4	*0.10*
Flat Lapping, Roughing*	12-20	*0.30-0.51*	12-20	*0.30-0.51*	12-20	*0.30-0.51*	12-20	*0.30-0.51*
Flat Lapping, Finishing*	6-11	*0.15-0.28*	6-11	*0.15-0.28*	6-11	*0.15-0.28*	6-11	*0.15-0.28*
Cylindrical Lapping*	7-9	*0.18-0.23*	7-9	*0.18-0.23*	7-9	*0.18-0.23*	—	—
Honing*	4-6	*0.10-0.15*	4-9	*0.10-0.23*	4-6	*0.10-0.15*	—	—
Super Finishing*	5-11	*0.13-0.28*	—	—	5-9	*0.13-0.23*	3-4	*0.08-0.10*

Table 6.3 **Surface finish in machined Ductile Irons.**

* Reference[4]

Material	Hardness BHN	Condition	Speed† fpm *m/min*	Feed† ipr or *mm/rev*, Nominal Hole Diameter: 1/16 in *1.5 mm*	1/8 in *3 mm*	1/4 in *6 mm*	1/2 in *12 mm*	3/4 in *18 mm*	1 in *25 mm*	1-1/2 in *35 mm*	2 in *50 mm*	Tool Material Grade AISI or C ISO
DUCTILE CAST IRONS ASTM A536: Grades 60-40-18, 65-45-12 SAE J434c: Grades D4018, D4512	140 to 190	Annealed	85 115 *26* *35*	.001 — *.025* —	.003 *.075*	.006 *.15*	.010 *.25*	.013 *.33*	.016 *.40*	.021 *.55*	.025 *.65*	M10, M7, M1 S2,S3
Ferritic-Pearlitic ASTM A536: Grade 80-55-06 SAE J434c: Grade D5506	190 to 225	As Cast	70 *21*	.001 *.025*	.003 *.075*	.006 *.15*	.010 *.25*	.013 *.33*	.016 *.40*	.021 *.55*	.025 *.65*	M10, M7, M1 S2,S3
	225 to 260	As Cast	50 *15*	.001 *.025*	.002 *.050*	.004 *.102*	.007 *.18*	.010 *.25*	.012 *.30*	.015 *.40*	.017 *.45*	T15, M42* S9, S11*
Pearlitic-Martensitic ASTM A536: Grade 100-70-03 SAE J434c: Grade D7003	240 to 300	Normalized and Tempered	45 *14*	.001 *.025*	.002 *.050*	.004 *.102*	.007 *.18*	.008 *.20*	.010 *.25*	.013 *.33*	.015 *.40*	T15, M42* S9, S11*
Martensitic ASTM A536: Grade 120-90-02 SAE J434c: Grade DQ&T	270 to 330	Quenched and Tempered	30 *9*	— —	.001 *.02?*	.002 *.050*	.004 *.102*	.005 *.13*	.006 *.15*	.007 *.18*	.008 *.20*	T15, M42* S9, S11*
	330 to 400	Quenched and Tempered	20 *6*	— —	.001 *.025*	.002 *.050*	.004 *.102*	.005 *.13*	.006 *.15*	.007 *.18*	.008 *.20*	T15, M42* S9, S11*
Austenitic (NI-RESIST) ASTM A439: Types D-2, D-2C, D-3A, D-5 ASTM A571: Type D-2M	120 to 200	Annealed	35 *11*	.001 *.025*	.002 *.050*	.005 *.13*	.007 *.18*	.010 *.25*	.012 *.30*	.015 *.40*	.018 *.45*	T15, M42* S9, S11*
Austenitic (NI-RESIST) ASTM A439: Types D-2B, D-3, D-4, D-5B	140 to 275	Annealed	25 *8*	.001 *.025*	.002 *.050*	.005 *.13*	.007 *.18*	.010 *.25*	.012 *.30*	.015 *.40*	.018 *.45*	T15, M42* S9, S11*

Table 6.4 **Starting recommendations for drilling Ductile Iron.**

do not present an unambiguous indication of the improved machinability of Ductile Iron, and it is instructive to use practical experience whenever possible. Experience gained by General Motors during the machining of ferritized Ductile Iron blanks for the production of ADI hypoid pinion-and-ring gears revealed improvements in tool life ranging from 20% to over 900%, compared to the annealed, forged steel blanks (Table 6.1). In addition to improved tool life and reduced tool costs, the improved machinability led to significant increases in productivity. Both laboratory and shop trials at Fiat (Table 6.2) on the machining of differential bevel gears revealed that, compared to a forged 18CrMo4 steel, ferritic Ductile Iron could be machined faster with less tool wear, resulting in increased productivity and reduced costs.

Hard Spots

Isolated "hard spots" in castings can seriously degrade machining performance. These areas of significantly increased hardness usually consist of carbides caused by localized rapid cooling and excess levels of carbide forming elements. Undissolved inoculant, oxides (slag), refractories, dross and burned-on moulding sand can also produce hard spots that are detrimental to machinability. Most hard spots can be eliminated by the use of good foundry practice: minimum levels of carbide forming elements (including magnesium and cerium), good inoculation, minimum holding times, correct pouring temperatures, good pouring practices, hard, expansion-resistant molds and good gating practices, including the use of gating system filters. Unavoidable hard areas in complex castings caused by rapid, localized cooling can be eliminated by annealing or normalizing heat treatments.

Surface Finish

Ductile Iron can be machined to produce a very fine surface finish, with the degree of finish depending on the fineness of the grain structure and the finishing method. With grinding and honing, a surface finish of four microinches or less is possible. Table 6.3 summarizes the surface finishes that can be obtained with various machining operations and different grades of Ductile Iron.

Coining

Coining is a specialized operation that can be used to both deform a Ductile Iron casting to produce its final shape, and shear off ingates, feeder necks and parting line "flash". Due to the strength of Ductile Iron, the size of casting that can be coined and the degree of deformation produced are limited. However, for small, high production castings that have been cast to near final shape and require limited further dimensional control and ingate and feeder neck removal, coining is a highly cost-effective operation that can eliminate certain machining operations.

Manufacturability Considerations

The machinability of a casting is an important component in its overall manufacturability, but there are other important considerations. Machining allowance affects productivity, yield and machining costs. Compared to steel castings, Ductile Iron requires reduced machining allowance for similar section sizes. Increased consistency of casting dimen-

Material	Hard-ness BHN	Condition	Depth of Cut* (in) mm	High Speed Steel Tool: Speed fpm m/min	High Speed Steel Tool: Feed ipr mm/r	High Speed Steel Tool: Tool Material AISI ISO	Carbide Tool, Uncoated: Speed Brazed fpm m/min	Carbide Tool, Uncoated: Speed Index-able fpm m/min	Carbide Tool, Uncoated: Feed ipr mm/r	Carbide Tool, Uncoated: Tool material Grade C ISO	Carbide Tool, Coated: Speed fpm m/min	Carbide Tool, Coated: Feed ipr mm/r	Carbide Tool, Coated: Tool Material Grade C ISO
DUCTILE CAST IRONS	140	Annealed	.040	200	.007	M2, M3	700	775	.010	C-7	950	.010	CC-7
Ferritic	to		.150	150	.015	M2, M3	550	600	.020	C-7	775	.020	CC-7
ASTM A536: Grades	190		.300	125	.020	M2, M3	450	500	.030	C-6	650	.030	CC-6
60-40-18, 65-45-12			.625	100	.030	M2, M3	360	400	.040	C-6	—	—	—
SAE J434c: Grades			*1*	*60*	*.18*	S4, S5	*215*	*235*	*.25*	P10, M10	*290*	*.25*	CP10, CM10
D4018, D4512			*4*	*46*	*.40*	S4, S5	*170*	*185*	*.50*	P10, M10	*225*	*.50*	CP10, CM10
			8	*38*	*.50*	S4, S5	*135*	*150*	*.75*	P20, M20	*200*	*.75*	CP20, CM20
			16	*30*	*.75*	S4, S5	*110*	*120*	*1.0*	P30, M30	—	—	—
Ferritic-Pearlitic	190	As Cast	.040	140	.007	M2, M3	480	540	.010	C-7	700	.010	CC-7
ASTM A536: Grade	to		.150	110	.015	M2, M3	375	425	.020	C-7	550	.020	CC-7
80-55-06	225		.300	85	.020	M2, M3	310	350	.030	C-6	450	.030	CC-6
SAE J434c: Grade 05506			.625	70	.030	M2, M3	250	275	.040	C-6	—	—	—
			1	*43*	*.18*	S4, S5	*145*	*165*	*.25*	P10, M10	*215*	*.25*	CP10, CM10
			4	*34*	*.40*	S4, S5	*115*	*130*	*.50*	P10, M10	*170*	*.50*	CP10, CM10
			8	*26*	*.50*	S4, S5	*95*	*105*	*.75*	P20, M20	*135*	*.75*	CP20, CM20
			16	*21*	*.75*	S4, S5	*76*	*84*	*1.0*	P30, M30	—	—	—
	225	As Cast	.040	100	.007	T15, M42†	320	360	.010	C-7	475	.010	CC-7
	to		.150	75	.015	T15, M42†	250	280	.020	C-7	350	.020	CC-7
	260		.300	60	.020	T15, M42†	200	230	.030	C-6	300	.030	CC-6
			.625	50	.030	T15, M42†	160	185	.040	C-6	—	—	—
			1	*30*	*.18*	S9, S11†	*100*	*110*	*.25*	P10, M10	*145*	*.25*	CP10, CM10
			4	*23*	*.40*	S9, S11†	*76*	*85*	*.50*	P10, M10	*105*	*.50*	CP10, CM10
			8	*18*	*.50*	S9, S11†	*60*	*70*	*.75*	P20, M20	*90*	*.75*	CP20, CM20
			16	*15*	*.75*	S9, S11†	*49*	*56*	*1.0*	P30, M30	—	—	—
Pearlitic Martensitic	240	Normalized	.040	75	.005	T15, M42†	260	300	.005	C-8	400	.005	CC-8
ASTM A536: Grade	to	and	.150	55	.010	T15, M42†	220	230	.010	C-7	300	.010	CC-7
100-70-03	300	Tempered	.300	45	.015	T15, M42†	160	190	.020	C-6	250	.020	CC-6
SAE J434c: Grade D7003			.625	35	.020	T15, M42†	130	150	.030	C-6	—	—	—
			1	*23*	*.13*	S9, S11†	*79*	*90*	*.13*	P10, M10	*120*	*.13*	CP01, CM10
			4	*17*	*.25*	S9, S11†	*67*	*79*	*.25*	P01, M10	*90*	*.25*	CP10, CM10
			8	*14*	*.40*	S9, S11†	*49*	*58*	*.50*	P20, M20	*76*	*.50*	CP20, CM20
			16	*11*	*.50*	S9, S11†	*40*	*46*	*.75*	P30, M30	—	—	—
Martensitic	270	Quenched	.040	50	.005	T15, M42†	175	200	.005	C-8	250	.005	CC-8
ASTM A536: Grade	to	and	.150	40	.010	T15, M42†	130	150	.010	C-7	200	.010	CC-7
120-90-02	330	Tempered	.300	30	.015	T15, M42†	110	125	.015	C-7	150	.015	CC-7
SAE J434c: Grade DQ&T			.625	—	—	—	—	—	—	—	—	—	—
			1	*15*	*.13*	S9, S11†	*53*	*60*	*.13*	P01, M10	*76*	*.13*	CP01, CM10
			4	*12*	*.25*	S9, S11†	*40*	*46*	*.25*	P10, M10	*60*	*.25*	CP10, CM10
			8	*9*	*.40*	S9, S11†	*34*	*38*	*.40*	P10, M10	*46*	*.40*	—
			16	—	—	—	—	—	—	—	—	—	—
	330	Quenched	.040	—	—	—	75	95	.003	C-8	—	—	—
	to	and	.150	—	—	—	55	70	.005	C-8	—	—	—
	400	Tempered	.300	—	—	—	45	60	.010	C-7	—	—	—
			1	—	—	—	*23*	*29*	*.075*	P01, M10	—	—	—
			4	—	—	—	*17*	*21*	*.13*	P01, M10	—	—	—
			8	—	—	—	*14*	*18*	*.25*	P10, M10	—	—	—
Austenitic (NI-RESIST Ductile)	120	Annealed	.040	70	.007	T15, M42†	225	250	.007	C-7	325	.007	CC-7
ASTM A439: Types D-2,	to		.150	60	.015	T15, M42†	160	175	.015	C-7	225	.015	CC-7
D-2C, D-3A, D-5	200		.300	50	.020	T15, M42†	125	140	.030	C-6	175	.020	CC-6
ASTM A571: Type D-2M			.625	35	.030	T15, M42†	100	115	.040	C-6	—	—	—
			1	*21*	*.18*	S9, S11†	*69*	*76*	*.18*	P10, M10	*100*	*.18*	CP10, CM10
			4	*18*	*.40*	S9, S11†	*49*	*53*	*.40*	P10, M10	*69*	*.40*	CP10, CM10
			8	*15*	*.50*	S9, S11†	*38*	*43*	*.75*	P20, M20	*53*	*.50*	CP20, CM20
			16	*11*	*.75*	S9, S11†	*30*	*35*	*1.0*	P20, M20	—	—	—

Table 6.5 **Starting recommendations for turning Ductile Iron with single point and box tools.**

SECTION VI

sions resulting from high density molding, and reduced surface defects can permit further decreases in machining allowance. Consistency of casting dimension is critical to obtaining the performance offered by modern automated machining centers. Consultation between the designer and foundry, the incorporation of manufacturability criteria in the purchase specifications, and the selection of a competent Ductile Iron foundry as a single source of consistent castings can significantly improve the manufacturability of the component and increase the value offered to the end user.

Machining Recommendations

Starting recommendations for the machining of Ductile Iron are summarized in Tables 6.4 – 6.8, obtained with permission from the Machining Data Handbook. For more complete data the reader should consult the first three references. Additional information on the machinability of Austempered Ductile Iron and Austenitic Ductile Iron can be found in Sections IV and V respectively.

REFERENCES

The Iron Castings Handbook, Iron Castings Society, Inc., 1981.

Machining Data Handbook, 3rd edition, Metcut Research Associates, Inc., Cincinnati, OH, 1980.

Metals Handbook, Vol. 16, 9th Edition, American Society for Metals, Metals Park, OH, 1967.

N. M. Lottridge and R. B. Grindahl, "Nodular Iron Hypoid Gears." Proceedings, SAE Conference on Fatigue, Dearborn, USA, 14-16 April, 1982. Society of Automotive Engineers, Warrendale PA, pp. 213-218.

S. Corso, "Development of bainitic nodular iron for the construction of speed gears for the car industry." EEC Commission Report EUR 8639.

M. Field and J. F. Kahles, "Factors Influencing Surface Finish in Turning and Milling of Gray and Ductile Irons," Society of Manufacturing Engineers, Dearborn, MI, 1971.

A. F. Ackenhausen and M. Field, "Determination and Analysis of Costs in N/C and Conventional Machining," SME Technical Paper, 1970.

"Machining Ductile Irons," International Nickel Co. Inc, New York, NY.

S. I. Karsay, Ductile Iron II, Quebec Iron and Titanium Corporation, 1972.

Machinery's Handbook, Industrial Press, 21st edition, New York, NY, 1979.

Tay-Forth Sales Limited, Private Communication, Stirlingshire, England, 1989.

K. B. Palmer, "The machinability of grey, nodular and compacted graphite irons compared by means of drilling tests," BCIRA Journal, January, 1983.

P. S. Cowen, "Coining Ductile Iron," Gray & Ductile Iron News, May, 1966.

Material	Hardness BHN	Condition	Depth of cut in *mm*	Speed fpm *m/min*	Feed ipr *mm/rev*	Type of Ceramic*
DUCTILE CAST IRONS	140	Annealed	.040	1200	.010	*HPC*
Ferritic	to		.150	1000	.015	*HPC*
ASTM A536: Grades 60-40-18, 65-45,12	190		.300	750	.025	*HPC*
SAE J434c: Grades D4018, D4512			*1*	*365*	*.25*	*HPC*
			4	*305*	*.40*	*HPC*
			8	*230*	*.65*	*HPC*
Ferritic-Pearlitic	*190*	*As Cast*	*.040*	*1100*	*.010*	*HPC*
ASTM A536: Grade 80-55-06	*to*		*.150*	*900*	*.015*	*HPC*
SAE J434c: Grade D5506	*225*		*.300*	*650*	*.020*	*HPC*
			1	*335*	*.25*	HPC
			4	*275*	*.40*	HPC
			8	*200*	*50*	HPC
	225	As Cast	.040	900	.005	HPC
	to		.150	700	010	HPC
	260		.300	550	.015	HPC
			1	*275*	*.13*	HPC
			4	*215*	*.25*	HPC
			8	*170*	*40*	HPC
Pearlitic-Martensitic	240	Normalized and	.040	800	.005	HPC
ASTM A536: Grade 100-70-03	to	Tempered	.150	600	010	HPC
SAE J434c Grade D7003	300		.300	450	.015	HPC
			1	*245*	*13*	HPC
			4	*185*	*25*	HPC
			8	*135*	*.40*	HPC
Martensitic	270	Quenched and	.040	750	.004	HPC
ASTM A536: Grade 120-90-02	to	Tempered	.150	550	.008	HPC
SAE J434c: Grade DQ&T	330		.300	400	.012	HPC
			1	*230*	*.102*	HPC
			4	*170*	*.20*	HPC
			8	*120*	*.30*	HPC
	330	Quenched and	.040	600	.003	HPC
	to	Tempered	.150	450	.006	HPC
	400		.300	350	.009	HPC
			1	*185*	*.075*	HPC
			4	*135*	*.15*	HPC
			8	*105*	*.23*	HPC
Austenitic (NI-RESIST Ductile)	120	Annealed	.040	1000	.005	HPC
ASTM A439: Types D-2, D-2C, D-3A, D-5	to		.150	700	.010	HPC
ASTM A571: Type D-2M	200		.300	450	.015	HPC
			1	*305*	*.13*	HPC
			4	*215*	*.25*	HPC
			8	*135*	*.40*	HPC

Table 6.6 **Starting recommendations for turning Ductile Iron with ceramic tools.**

Material	Hardness BHN	Condition	Depth of Cut* in mm	High Speed Steel Tool: Speed fpm m/min	High Speed Steel Tool: Feed per tooth in mm	High Speed Steel Tool: Tool Material AISI ISO	Carbide Tool, Uncoated: Speed Brazed fpm m/min	Carbide Tool, Uncoated: Speed Indexable fpm m/min	Carbide Tool, Uncoated: Feed per Tooth in mm	Carbide Tool, Uncoated: Tool Material Grade C ISO	Carbide Tool, Coated: Speed fpm m/min	Carbide Tool, Coated: Feed per Tooth in mm	Carbide Tool, Coated: Tool Material Grade C ISO
DUCTILE CAST IRONS	140	Annealed	.040	195	.010	M2, M7	665	730	.010	C-6	1100	.008	CC-6
Ferritic	to		.150	150	.014	M2, M7	500	550	.015	C-6	715	.012	CC-6
ASTM A536: Grades	190		.300	115	.018	M2, M7	350	430	.020	C-6	560	.016	CC-6
60-40-18, 65-45-12			*1*	*59*	*.25*	S4, S2	*205*	*225*	*.25*	M20, P20	*335*	*.20*	CM20, CP20
SAE J431c: Grades			*4*	*46*	*.36*	S4, S2	*150*	*170*	*.40*	M30, P30	*220*	*.30*	CM30, CP30
D4018, D4512			*8*	*35*	*.45*	S4, S2	*105*	*130*	*.50*	M40, P40	*170*	*.40*	CM40, CP40
Ferritic-Pearlitic	190	As Cast	.040	145	.008	M2, M7	465	510	.008	C-6	765	.008	CC-6
ASTM A536: Grade	to		.150	110	.012	M2, M7	350	385	.012	C-6	500	.012	CC-6
80-55-06	225		.300	85	.016	M2, M7	245	300	.016	C-6	400	.016	CC-6
SAE J434c: Grade			*1*	*44*	*.20*	S4, S2	*140*	*155*	*.20*	M20, P20	*235*	*.20*	CM20, CP20
D5506			*4*	*34*	*.30*	S4, S2	*105*	*115*	*.30*	M30, P30	*150*	*.30*	CM30, CP30
			8	*26*	*.40*	S4, S2	*75*	*90*	*.40*	M40, P40	*120*	*.40*	CM40, CP40
	225	As Cast	.040	115	.008	M2, M7	400	440	.007	C-6	650	.007	CC-6
	to		.150	90	.012	M2, M7	310	330	.010	C-6	425	.010	CC-6
	260		.300	70	.016	M2, M7	210	255	.014	C-6	325	.014	CC-6
			1	*35*	*.20*	S4, S2	*120*	*135*	*.18*	M20, P20	*200*	*.18*	CM20, CP20
			4	*27*	*.30*	S4, S2	*95*	*100*	*.25*	M30, P30	*130*	*.25*	CM30, CP30
			8	*21*	*.40*	S4, S2	*64*	*78*	*.36*	M40, P40	*100*	*.36*	CM40, CP40
Pearlitic-	240	Normalized	.040	85	.006	M2, M7	320	350	.006	C-6	525	.005	CC-6
Martensitic	to	and	.150	65	.010	M2, M7	240	265	.008	C-6	350	.007	CC-6
ASTM A536: Grade	300	Tempered	.300	50	.014	M2, M7	170	205	.010	C-6	275	.009	CC-6
100-70-03			*1*	*26*	*.15*	S4, S2	*100*	*105*	*.15*	M20, P20	*160*	*.13*	CM20, CP20
SAE J434c: Grade			*4*	*20*	*.25*	S4, S2	*73*	*81*	*.20*	M30, P30	*105*	*.18*	CM30, CP30
D7003			*8*	*15*	*.36*	S4, S2	*52*	*62*	*.25*	M40, P40	*84*	*.23*	CM40, CP40
Martensitic	270	Quenched	.040	45	.006	T15, M42†	190	210	.006	C-6	315	.005	CC-6
ASTM A536: Grade	to	and	.150	35	.010	T15, M42†	140	155	.008	C-6	200	.007	CC-6
120-90-02	330	Tempered	.300	25	.014	T15, M42†	100	120	.010	C-6	150	.009	CC-6
SAE J434c: Grade			*1*	*14*	*.15*	S9, S11†	*58*	*64*	*.15*	M20, P20	*95*	*.13*	CM20, CP20
DQ&T			*4*	*11*	*.25*	S9, S11†	*43*	*47*	*.20*	M30, P30	*60*	*.18*	CM30, CP30
			8	*8*	*.36*	S9, S11†	*30*	*37*	*.25*	M40, P40	*46*	*.23*	CM40, CP40
	330	Quenched	.040	—	—	—	90	100	.004	C-6	—	—	—
	to	and	.150	—	—	—	70	80	.006	C-6	—	—	—
	400	Tempered	.300	—	—	—	50	60	.008	C-6	—	—	—
			1	—	—	—	*27*	*30*	*.102*	M20, P20	—	—	—
			4	—	—	—	*21*	*24*	*.15*	M30, P30	—	—	—
			8	—	—	—	*15*	*19*	*.20*	M40, P40	—	—	—
Austenitic	120	Annealed	.040	40	.008	T15, M42†	175	195	.008	C-6	290	.008	CC-6
(NI-RESIST Ductile)	to		.015	25	.012	T15, M42†	100	110	.012	C-6	140	.012	CC-6
ASTM A439: Types D-2,	200		.300	20	.016	T15, M42†	70	85	.016	C-6	110	.016	CC-6
D-2C, D-3A, D-5			*1*	*12*	*.20*	S9, S11†	*53*	*59*	*.20*	M20, P20	*88*	*.20*	CM20, CP20
ASTM A571: Type D-2M			*4*	*8*	*.30*	S9, S11†	*30*	*34*	*.30*	M30, P30	*43*	*.30*	CM30, CP30
			8	*6*	*.40*	S9, S11†	*21*	*26*	*.40*	M40, P40	*34*	*.40*	CM40, CP40
Austenitic	140	Annealed	.040	30	.006	T15, M42†	120	135	.007	C-6	200	.007	CC-6
(NI-RESIST Ductile)	to		.150	20	.010	T15, M42†	80	90	.010	C-6	115	.010	CC-6
ASTM A439: Types	275		.300	15	.014	T15, M42†	60	70	.014	C-6	90	.014	CC-6
D-2B, D-3, D-4, D-5B			*1*	*9*	*.15*	S9, S11†	*37*	*41*	*.18*	M20, P20	*60*	*.18*	CM20, CP20
			4	*6*	*.25*	S9, S11†	*24*	*27*	*.25*	M30, P30	*35*	*.25*	CM30, CP30
			8	*5*	*.36*	S9, S11†	*18*	*21*	*.36*	M40, P40	*30*	*.36*	CM40, CP40

Table 6.7 Starting recommendations for face milling Ductile Iron.

SECTION VI

Material	Hardness BHN	Condition	Depth of Cut* in *mm*	Speed fpm *m/min*	Feed/ Tooth in *mm*	HSS Tool Material AISI ISO
DUCTILE CAST IRONS Ferritic ASTM A536: Grades 60-40-18, 65-45-12 SAE J434c: Grades D4018, D4512	140 to 190	Annealed	.040 .150 .300	190 145 115	.010 .012 .014	M2, M7
			1 *4* *8*	*58* *44* *35*	*.25* *.30* *.36*	S4, S2
Ferritic-Pearlitic ASTM A536: Grade 80-55-06 SAE J434c: Grade D5506	190 to 225	As Cast	.040 .150 .300	125 95 75	.008 .010 .012	M2, M7
			1 *4* *8*	*38* *29* *23*	*.20* *.25* *.30*	S4, S2
	225 to 260	As Cast	.040 .150 .300	110 85 65	.006 .008 .010	M2, M7
			1 *4* *8*	*34* *26* *20*	*.15* *.20* *.25*	S4, S2
Pearlitic-Martensitic ASTM A536: Grade 100-70-03 SAE J434c: Grade D7003	240 to 300	Normalized and Tempered	.040 .150 .300	80 60 45	.006 .008 .010	M2, M7
			1 *4* *8*	*24* *18* *14*	*.15* *.20* *.25*	S4, S2
Martensitic ASTM A536: Grade 120-90-02 SAE J434c: Grade DQ&T	270 to 330	Quenched and Tempered	.040 .150 .300	40 30 20	.005 .006 .007	M2, M7
			1 *4* *8*	*12* *9* *6*	*.13* *.15* *.18*	S4, S2
Austenitic (NI-RESIST Ductile) ASTM A439: Types D-2, D-2C, D-3A, D-5 ASTM A571: Type D-2M	120 to 200	Annealed	.040 .150 .300	35 20 15	.005 .007 .009	M2, M7
			1 *4* *8*	*11* *6* *5*	*.13* *.18* *.23*	S4, S2
Austenitic (NI-RESIST Ductile) ASTM A439: Types D-2B, D-3, D-4, D-5B	140 to 275	Annealed	.040 .150 .300	25 15 10	.005 .007 .009	M2, M7
			1 *4* *8*	*8* *5* *3*	*.13* *.18* *.23*	S4, S2

Table 6.8 **Starting recommendations for slab milling Ductile Iron.**

SECTION VI

SECTION VII

HEAT TREATMENT

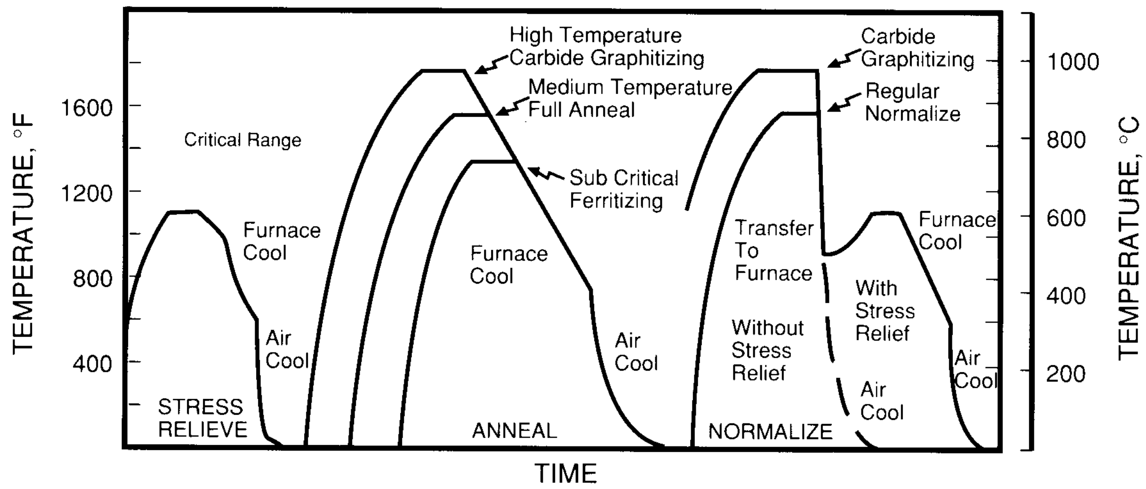
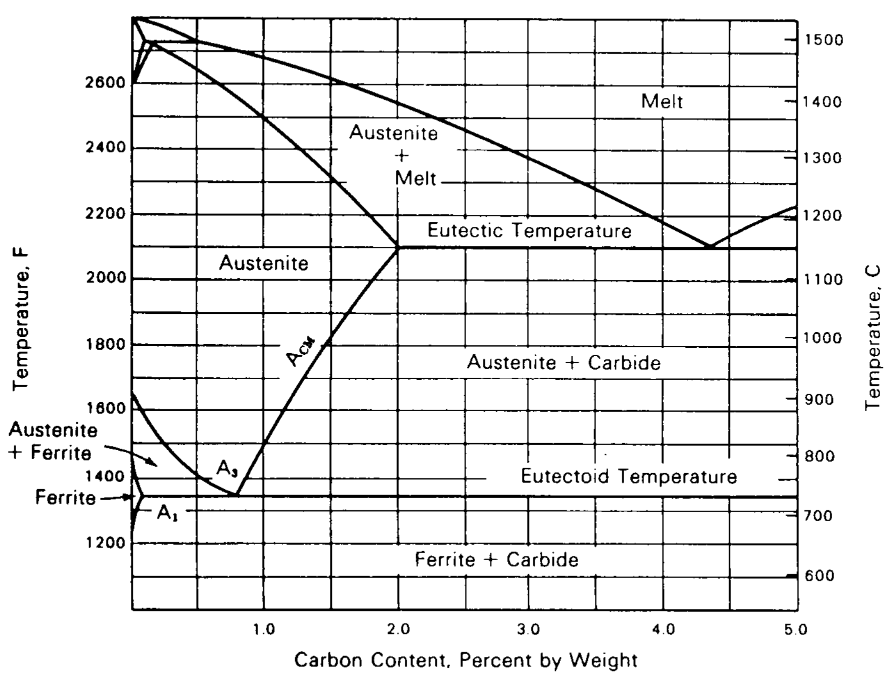


Figure 7.1 Examples of different heat treatments used to relieve stresses, anneal and normalize Ductile Iron castings.

Figure 7.2



The iron-iron carbide binary equilibrium diagram.

HEAT TREATMENT

Introduction

One reason for the phenomenal growth in the use of Ductile Iron castings is the high ratio of performance to cost that they offer the designer and end user. This high value results from many factors, one of which is the control of microstructure and properties that can be achieved in the as-cast condition, enabling a high percentage of ferritic and pearlitic Ductile Iron castings to be produced without the extra cost of heat treatment. To obtain the advantage of producing high quality castings as-cast requires the use of consistent charge materials and the implementation of consistent and effective practices for melting, holding, treating, inoculation and cooling in the mold. By following these practices, especially the use of high purity charges and late inoculation, castings can be produced as-cast essentially free of carbides and with pearlite contents less than 10%, in section sizes as low as 0.150 in. (3.8 mm).

However heat treatment is a valuable and versatile tool for extending both the consistency and range of properties of Ductile Iron castings well beyond the limits of those produced in the as-cast condition. Thus, to utilize fully the potential of Ductile Iron castings, the designer should be aware of the wide range of heat treatments available for Ductile Iron, and its response to these heat treatments.

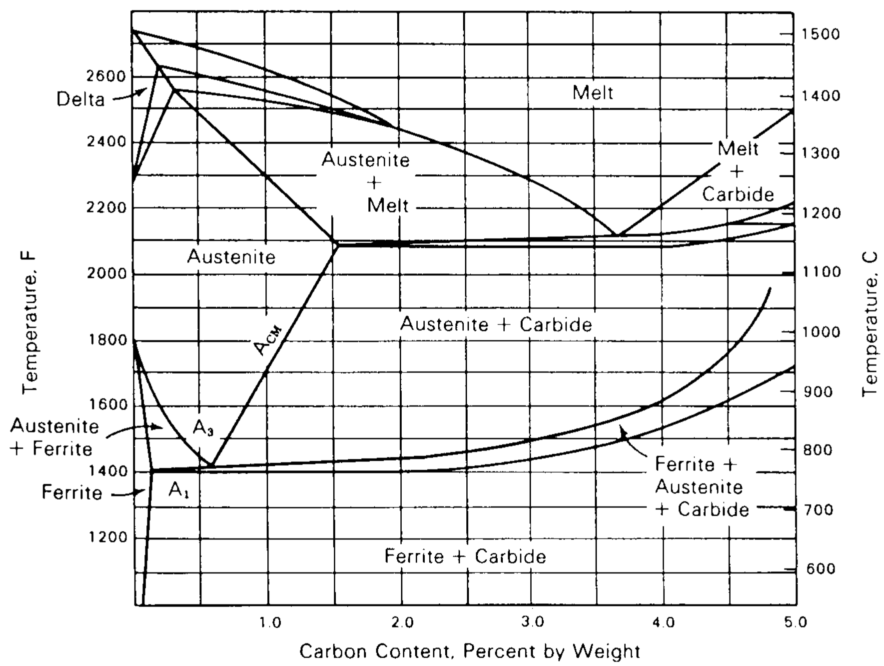
Ductile Iron castings may be heat treated to:

- increase toughness and ductility,
- increase strength and wear resistance,
- increase corrosion resistance,
- stabilize the microstructure, to minimize growth,
- equalize properties in castings with widely varying section sizes,
- improve consistency of properties,
- improve machinability, and
- relieve internal stresses.

This Section deals with heat treating conventional Ductile Iron. Austempering heat treatments, and the heat treatment of alloy Ductile Irons, are discussed in Sections IV and V.

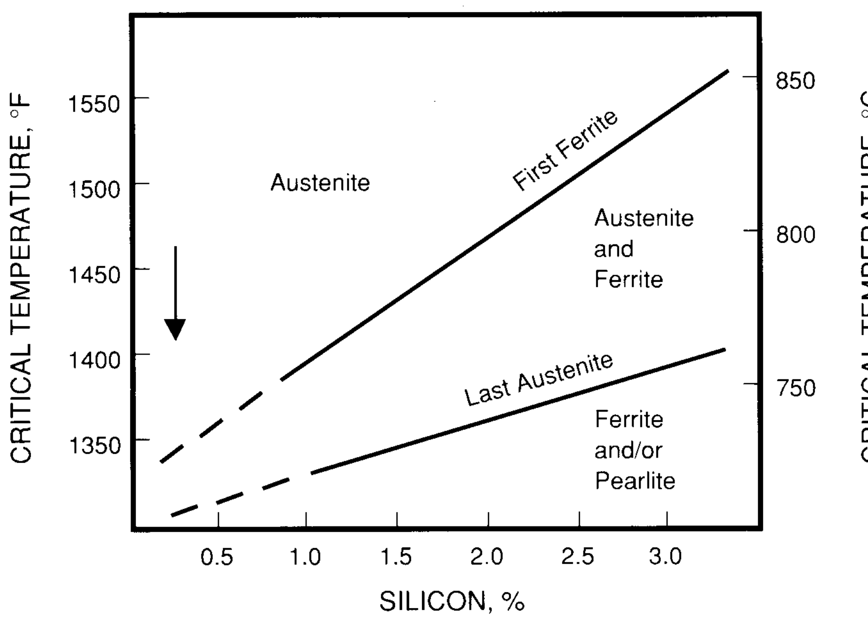
Although Ductile Iron and steel are superficially similar metallurgically, the high carbon and silicon levels in Ductile Iron result in important differences in their response to heat treatment. The higher carbon levels in Ductile Iron increase hardenability, permitting heavier sections to be heat treated with lower requirements for expensive alloying or

Figure 7.3



The iron-iron carbide-silicon ternary diagram sectioned at 2 per cent silicon.

Figure 7.4



The effect of silicon on the critical temperature range for slow-cooled cast iron.

severe quenching media. These higher carbon levels can also cause quench cracking due to the formation of higher carbon martensite, and/or the retention of metastable austenite. These undesirable phenomena make the control of composition, austenitizing temperature and quenching conditions more critical in Ductile Iron. Silicon also exerts a strong influence on the response of Ductile Iron to heat treatment. The higher the silicon content, the lower the solubility of carbon in austenite and the more readily carbon is precipitated as graphite during slow cooling to produce a ferritic matrix.

Although remaining unchanged in shape, the graphite spheroids in Ductile Iron play a critical role in heat treatment, acting as both a source and sink for carbon. When heated into the austenite temperature range, carbon readily diffuses from the spheroids to saturate the austenite matrix. On slow cooling the carbon returns to the graphite ''sinks'', reducing the carbon content of the austenite. This availability of excess carbon and the ability to transfer it between the matrix and the nodules makes Ductile Iron easier to heat treat and increases the range of properties that can be obtained by heat treatment.

Critical Temperature

All Ductile Iron heat treatments, apart from stress relief, tempering and subcritical annealing, involve heating the casting to a temperature above the critical temperature range (Figure 7.1). In ferrous heat treatment, the critical temperature (A_1) is the temperature above which the austenite phase is stable. Unlike steels, which have a constant critical temperature (eutectoid temperature), Figure 7.2, Ductile Irons are ternary, iron-carbon-silicon alloys in which the critical temperature varies with both carbon and silicon contents. Figure 7.3 shows the effect of carbon on this ternary phase diagram at the 2% silicon level. Figure 7.4 shows the effect of silicon on the critical temperatures for typical cast irons. This relationship, the desired carbon content in the austenite and the need to dissolve carbides, are the primary determinants of the correct austenitizing temperature for Ductile Iron.

Controlled Shakeout

The most simple and economic form of heat treatment is the controlled shakeout of the castings from the mold. By removing the castings from the mold above the critical temperature, the rate of cooling can be increased, favouring the formation of pearlite with a resultant increase in casting hardness and strength (Figure 7.5). If the alloy content is sufficiently high, castings with bainitic structures can also be produced by this method. Hardening castings through early shakeout requires extremely close control of shakeout times and casting composition and immediate stress relief of complex castings to avoid the detrimental effects of internal stresses.

Austenitizing

Austenitizing is the process of holding the Ductile Iron casting above the critical temperature for a sufficient period of time to ensure that the matrix is fully transformed to austenite. The austenitizing temperature, along with the silicon content, determines the carbon content of the austenite. Both austenitizing time and temperature depend on the microstructure and composition of the as-cast material. In order to break down primary carbides, austenitizing temperatures in the range 1650-1750 °F (900-940 °C) are normally used, with times ranging from one to three hours. High silicon content and high nodule count reduce breakdown times, while the presence of carbide stabilizers such as chromium, vanadium and molybdenum require substantially longer times. Pearlite decomposition occurs much more rapidly and at lower temperatures than carbide breakdown. It is enhanced by high silicon and high nodularity and retarded by pearlite stabilizing elements such as manganese, copper, tin, antimony and arsenic. The segregation of manganese and chromium to cell boundaries can result in the incomplete dissolution of both pearlite and carbides and the resulting impairment of mechanical properties.

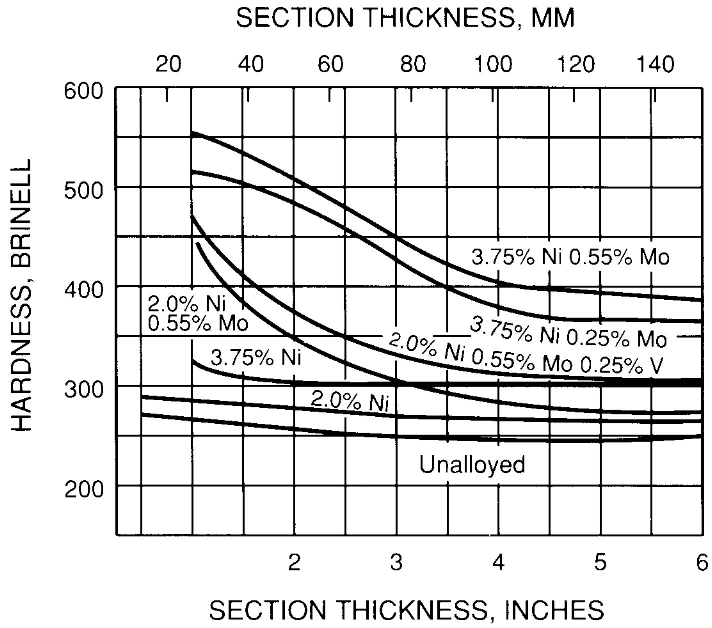
Annealing

Annealing softens Ductile Iron by producing a carbide-free, fully ferritic matrix. Table 7.1 describes recommended practices for annealing Ductile Iron. These procedures range from a low temperature or sub-critical anneal used to ferritize carbide-free castings, to two-stage and high temperature anneals designed to break down carbides. The primary purpose of annealing, or ferritizing, Ductile Iron is the production of castings with maximum ductility and toughness, reduced strength and hardness, improved machinability and uniform properties. Figure 3.17 (Section 3) shows that annealing castings with different levels of copper and tin has reduced strength and hardness, increased elongation, and generally eliminated the variations in as-cast properties produced by the different alloy levels (Figure 3.16). Figures 3.44, 3.51 and Table 3.4 illustrate the effects of both standard and subcritical annealing on the fracture toughness of Ductile Iron.

Normalizing

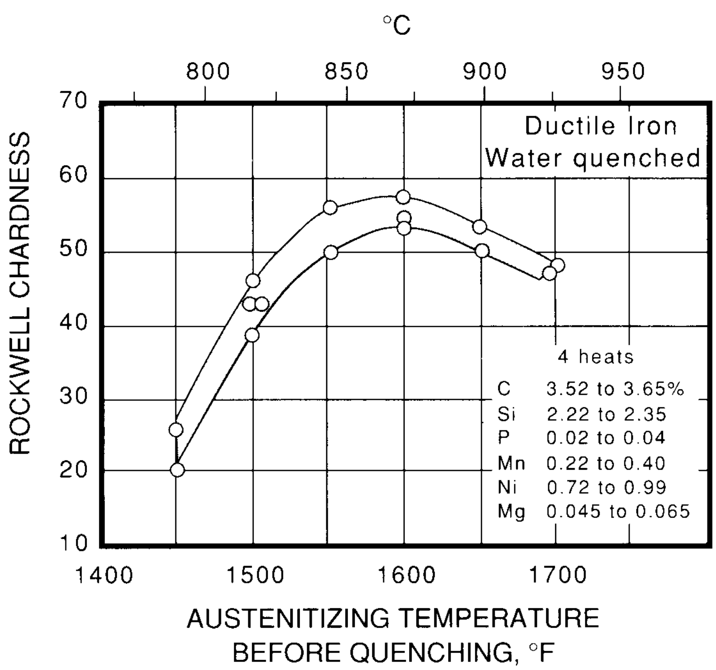
Normalizing involves the austenitizing of a Ductile Iron casting, followed by cooling in air through the critical temperature. An as-cast Ductile Iron casting is normalized in order to: break down carbides, increase hardness and strength, and produce more uniform properties (see Figures 3.16 and 3.18). Normalizing should be carried out at an austenitizing temperature approximately 100°C (212°F) above the critical temperature range. Typically, austenitizing temperatures in the range 1600-1650°F (870-900°C) and holding times of one hour, plus one hour per inch of casting thickness, are adequate to produce a fully austenitic structure in unalloyed castings relatively free of carbide. The cooling rate should be sufficiently rapid to suppress ferrite formation and produce a fully pearlitic structure. Depending on casting section size and alloy content, adequate cooling rates can be achieved in still air, or large fans may be required. If fan cooling cannot produce the desired pearlitic structure, the castings should be alloyed with pearlite stabilizing elements such as copper, tin, nickel or antimony. Figure 7.6 illustrates the effect of alloy content and section size on the hardness of normalized Ductile Iron. Step normalizing, which employs a second,

Figure 7.6



The effect of section thickness and composition on the hardness of Ductile Iron castings.

Figure 7.7



The influence of austenitizing temperature on the hardness of water quenched Ductile Iron.

SECTION VIII

lower temperature stage prior to air cooling, can be used to provide the improved matrix control required for the production of pearlitic/ferritic grades of Ductile Iron.

Quench Hardening

Maximum hardness in Ductile Iron castings is obtained by austenitizing, followed by quenching sufficiently rapidly to suppress the formation of both ferrite and pearlite, to produce a metastable austenite which transforms to martensite at lower temperature. As-quenched hardness depends on the carbon content of the martensite and the volume fraction of martensite in the matrix. In conjunction with the silicon content, the austenitizing temperature determines the carbon content of the austenite. For a silicon content of approximately 2.5%, an austenitizing temperature of 1650 °F (900 °C) will result in the optimum carbon content and maximum hardness (Figure 7.7). Lower temperatures, 1475-1550 °F (800-845 °C), will produce a low carbon austenite which, on cooling, will transform to a softer martensite.

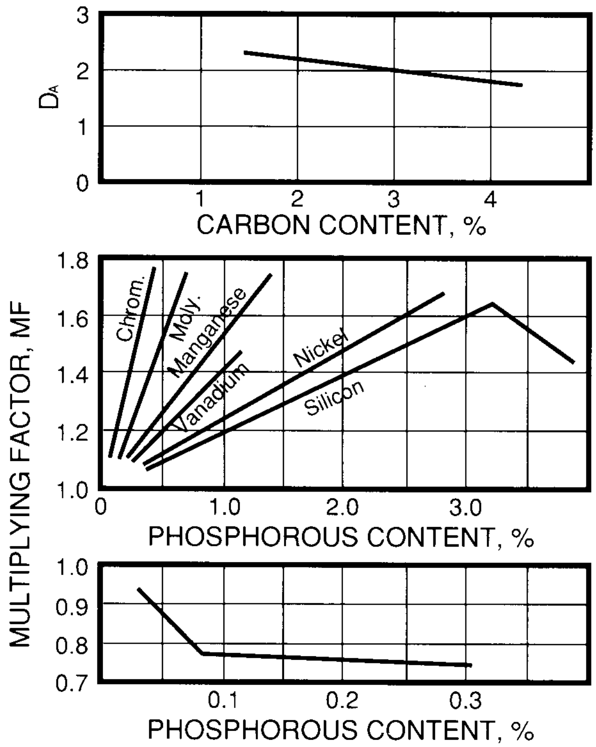
The formation of low carbon martensite will cause reduced distortion and cracking in complex castings during quenching and, when tempered, low carbon martensite has toughness superior to both tempered high carbon martensite and normalized microstructures (see Figure 3.44, Section III). Higher austenitizing temperatures increase the carbon content of the austenite but the bulk hardness is reduced due to retained austenite and a lower resultant martensite content. Regardless of the austenitizing and quenching conditions, quenched Ductile Iron castings must be tempered before use to eliminate internal stresses, control strength and hardness and provide adequate ductility.

Hardenability

Hardenability is a measure of how rapidly the Ductile Iron casting must be cooled in order to suppress the ferrite and pearlite transformations and produce a martensitic, bainitic or austempered matrix. Hardenability is an important property of any casting that is to be quench hardened because it determines the depth to which a fully or partially martensitic matrix can be produced and the severity of quench required to harden castings of different section size. The effects of various alloying elements on the hardenability of Ductile Iron are illustrated in Figure 7.8. To calculate the hardenability of a casting the absolute hardenability (D_A), based on the carbon content, is first determined. The ideal critical diameter (D_I) is then calculated by multiplying D_A by the multiplying factors determined from Figure 7.8 for each alloying element. For example, a Ductile Iron of the composition:

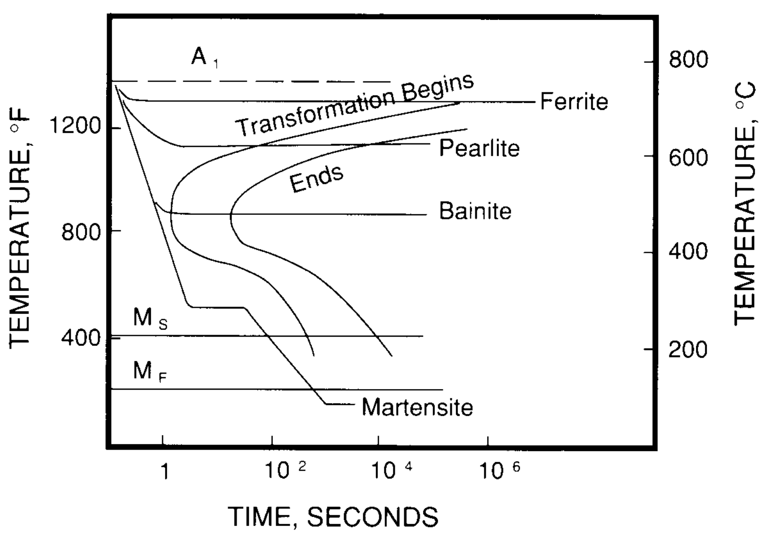
Total Carbon, %	3.60	D_A = 2.00
Silicon, %	2.50	MF = 1.50
Manganese, %	0.35	MF = 1.15
Phosphorus, %	0.07	MF = 0.80
Nickel, %	1.00	MF = 1.25

Figure 7.8



The influence of carbon and various alloying elements on the hardenability of Ductile Iron.

Figure 7.9



Typical TTT diagram for a low silicon Gray Iron.

SECTION VII

the ideal critical diameter would be calculated as follows:

$$D_I = D_A \times (MF_{Si}) \times (MF_{Mn}) \times (MF_P) \times (MF_{Ni})$$
$$= 3.45 \text{ inches (88 mm)}.$$

Thus, for the composition used in this example, a 3.45 in. (88 mm) diameter bar, when quenched in water, will have a matrix containing 50% martensite at the bar center.

Alloying elements for quenched and tempered Ductile Iron should not be selected on the basis of hardenability alone. Chromium, which is extremely effective in promoting hardenability, is very detrimental to Ductile Iron quality because it increases the formation of carbides in the as-cast state. Manganese not only promotes the formation of carbides but also retards the tempering process. Thus, for both metallurgical and economic reasons, alloying elements should be selected carefully and used at the lowest levels which provide the desired hardenability.

TTT Diagrams

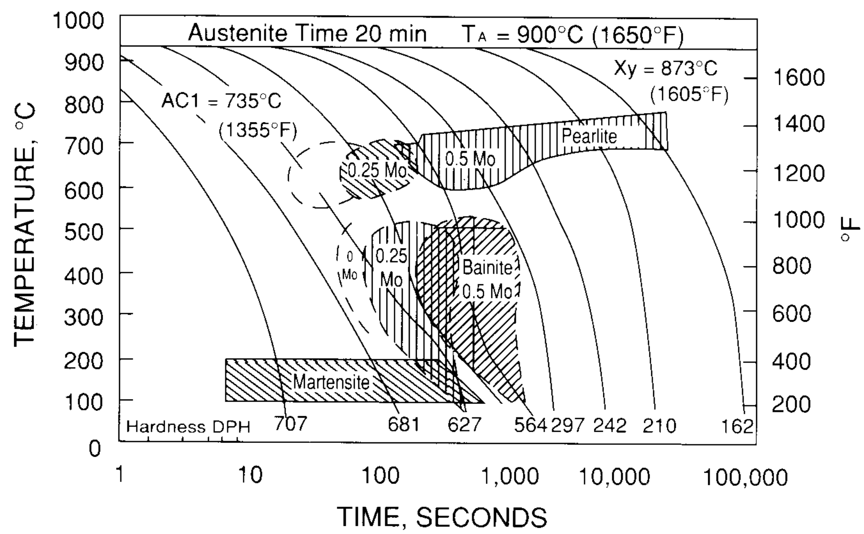
TTT (time, temperature, transformation) diagrams are also useful in selecting heat treatment practices for Ductile Irons. Figure 7.9 shows a typical TTT diagram for a low silicon gray iron. Each cooling path in this Figure defines the time-temperature cooling relationship required to produce a specific microstructure. The position of the transformation zone on the TTT diagram, defined by start and finish curves, determines the rate and extent of cooling required to avoid certain transformations and promote others. To ensure that a quenched component is entirely martensitic, the slowest cooling rate must be sufficiently fast to avoid the "nose" of the transformation zone.

Each composition of iron has a unique TTT diagram, with the location of the transformation zone controlled by the composition (Figure 7.10). In this Figure the influence of molybdenum on the various transformations reveals why it has a high hardenability multiplying factor (Figure 7.8). Increasing molybdenum content shifts the transformation zones to the right, allowing complete transformation to martensite at the slower cooling rates found in larger casting section sizes. Knowledge of the many TTT diagrams published for Ductile Iron enables the foundry and heat treater to select appropriate alloy contents and quenching conditions to produce suitably hardened castings.

Quenching Media

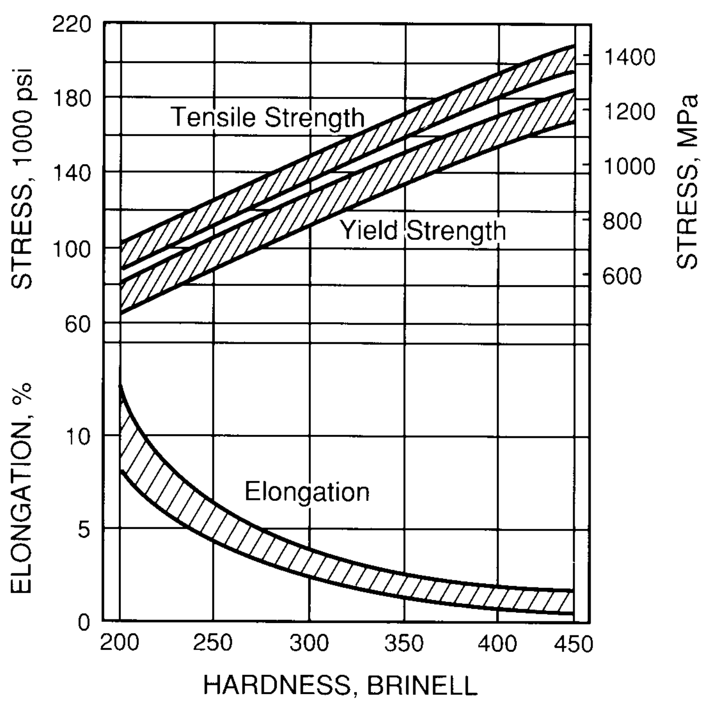
The quenching medium and the degree of agitation in the quench bath are important variables that can be used to ensure that a suitable microstructure is produced by the quenching process. Common quench media, in order of increasing severity are oil, water and brine. Agitation of the quenching bath may be required to increase both quench severity and the uniformity of cooling in complex castings or batches of castings. To minimize internal stresses, distortion and cracking, especially in complex castings, the least severe quenching medium that produces

Figure 7.10



The effect of molybdenum content on the TTT diagram for Ductile Iron.

Figure 7.11



Tensile and hardness properties for quenched and tempered Ductile Iron.

SECTION VII

the desired microstructure should be selected. As the required severity of quenching increases, it becomes increasingly important to temper the castings immediately after quenching.

Tempering

Tempering reduces the strength and hardness and increases the ductility, toughness and machinability of quenched or normalized Ductile Iron. In addition, tempering quenched castings also reduces residual stresses, decreases the amount of retained austenite, and reduces the probability of cracking. These changes in properties are achieved by holding the castings at a temperature that is below the critical temperature. Tempering is a diffusional process and thus is time and temperature dependent. Tempering conditions are influenced strongly by the desired change in properties, the alloy content, the microstructure being tempered and the nodule count. Low alloy content, martensitic structures and high nodule count reduce tempering temperatures and/or times, while high alloy content, a normalized (pearlitic) structure and low nodule count increase tempering times.

Normalize and Temper

Castings may be tempered after normalizing to provide an optimum combination of high strength and toughness. This process also provides the additional advantage of improving the control of properties through selection of tempering temperature and time.

Quench and Temper

Quenching and tempering are the standard heat treatments applied to Ductile Iron castings requiring maximum strength and wear resistance. In addition to maximizing strength, these treatments can provide close control of casting properties over a wide range of strength and ductility, and optimum combinations of strength and toughness (see Figure 3.44). Figure 7.11 illustrates the wide range of properties of quenched and tempered Ductile Iron castings that can be obtained through selection of the appropriate tempering temperature (Figure 7.12).

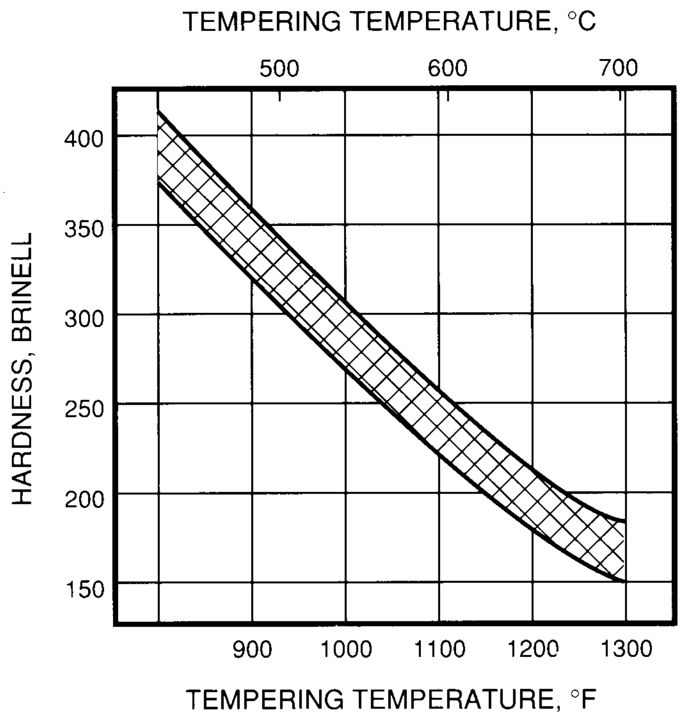
Temper Embrittlement

Temper embrittlement, a type of embrittlement found in certain quenched and tempered steels, may also occur in similarly treated Ductile Irons with susceptible compositions. This form of embrittlement, which does not affect normal tensile properties but causes significant reductions in fracture toughness, can occur in Ductile Irons containing high levels of silicon and phosphorus which have been tempered in the range 650-1100°F (350-600°C) and cooled slowly after tempering. Although normally associated with tempered martensite, temper embrittlement can also occur if the matrix is tempered to the fully ferritic condition. Temper embrittlement can be prevented by keeping silicon and phosphorus levels as low as possible, adding up to 0.15 per cent molybdenum and avoiding the embrittling heat treating conditions.

Secondary Graphite

The formation of secondary graphite during the tempering of martensitic Ductile Iron can be responsible for both the degradation and increased variability of mechanical properties. Secondary graphitization

Figure 7.12



The effect of tempering temperature on the hardness of oil-quenched Ductile Iron. The initial hardness was 570 BHN and the tempering time was 2 hours.

SECTION VII

is favoured by high austenitizing and tempering temperatures and high levels of silicon, copper and nickel. Like temper embrittlement, the use of small additions of molybdenum can eliminate this problem. To further prevent its occurrence, the tempering of martensitic Ductile Irons to hardnesses below 270 BHN, which require high temperature tempering, should be avoided.

Surface Hardening

Ductile Iron can be surface hardened by flame or induction heating of the casting surface layer to about 1650 °F (900 °C), followed by a quenching spray. Hardness levels as high as HRC 60 can be achieved by these procedures, producing a highly wear resistant surface backed by a tough, ductile core. Pearlitic grades of Ductile Iron, which have an intimate mixture of lamellar carbide and ferrite, respond most effectively to surface hardening due to their reduced diffusion distances.

Residual Stresses

The presence of residual stresses can be detrimental to both the production and performance of Ductile Iron castings. If sufficiently severe, residual stresses can cause castings to distort and crack even during normal handling. Lower residual stresses can cause the casting to distort during subsequent heat treatment or machining. Residual stresses can also result in premature yielding or fracture when the casting is used in an applied stress environment that should have ensured safe operation.

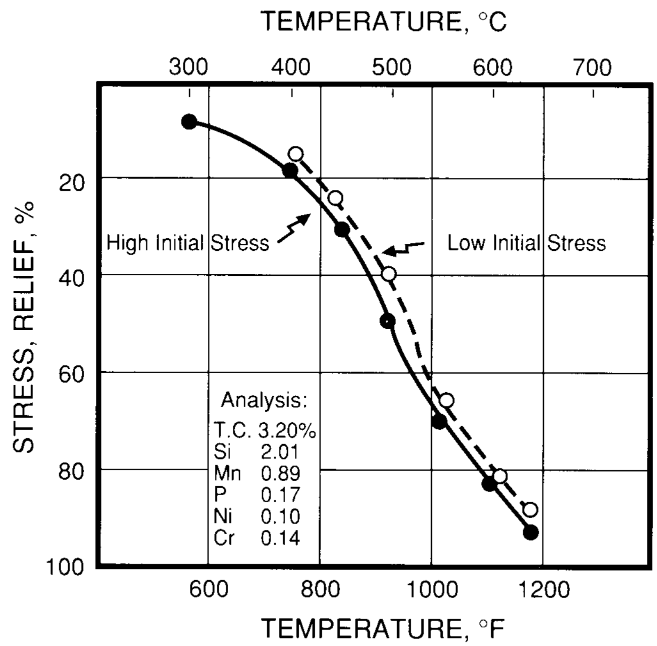
Both the occurrence and the effects of residual stresses in castings vary according to the design of the casting, production procedures, and the end use of the casting. Large, heavy section, or ''chunky'' (all dimensions approximately equal) Ductile Iron castings are usually stress free as-cast and require no subsequent stress relief. Complex castings with large variations in section size or constrained thin castings are more likely to contain residual stresses requiring stress relief. Sand molds are good insulators and even complex castings may cool sufficiently slowly to prevent the development of significant residual stresses. However, the premature ''shakeout'' of castings from molds can cause severe residual stresses, in addition to variations in hardness.

Rigid molds and cores may prevent normal metal contraction during cooling and result in residual casting stresses. Subsequent processing such as shot peening, welding, heat treatment or surface hardening, if not performed properly, can induce significant residual stresses that may become evident during machining or subsequent use of the casting.

Stress Relief

Stress relief is achieved by heating the casting to a sufficiently high temperature that its strength is reduced to the extent that the residual stress can be relieved by plastic deformation. The extent to which stresses will be relieved or eliminated is dependent on several factors, including the initial severity of the residual stresses, the stress relieving time and temperature, the heating-cooling cycle, and the composition and micros-

Figure 7.13



The effect of initial stress level and stress relieving temperature on the percentage of stress that is relieved in 1 hour at the indicated temperature.

tructure of the casting. Figure 7.13 shows that stress relief is proportional to the level of initial stress, and that the degree of stress relief is strongly temperature dependent. After stress relief a uniform rate of cooling must be maintained throughout the casting to prevent the reintroduction of stresses. This is normally accomplished by cooling in the furnace from the stress relieving temperature to approximately 800°F (430°C). For complex castings, and where the greatest degree of stress relief is desired, furnace cooling to 300°F (150°C) is recommended. The heating rate may be as important as the cooling rate in the prevention of internal stresses, especially for complex or highly stressed castings. Placing such castings in a hot furnace will result in differential thermal stresses that could cause distortion during the subsequent heat treatment.

Scaling, Growth and Distortion

Scaling, growth and distortion of castings during heat treatment should be considered in order to minimize the detrimental effects of these phenomena. Scaling, which increases with time and temperature, can be eliminated by the use of a controlled atmosphere furnace. An overall increase in casting dimensions may occur during heat treatment due to the graphitization of eutectic carbides and the conversion of pearlite to ferrite. At austenitizing temperatures Ductile Iron castings have very low strength and will easily sag and distort if not properly supported. To reduce the risk of distortion, austenitizing time and temperature should be kept to the minimum required to ensure complete carbide breakdown and austenitization of the matrix.

Best properties

The as-cast structures of Ductile Iron are easily obtained by using **Sorelmetal** for production. The resultant properties and specially the fatigue strength would be better in this condition.

REFERENCES

J. E. Rehder, "Critical Temperature Heat Treatment of Cast Irons," Foundry, June, 1965.

L. J. Ebert and J. F. Wallace, "How Composition Affects the Properties of Ductile Iron," Metal Progress, December, 1961.

The Iron Castings Handbook, Iron Castings Society, Inc., 1981.

W.H. Browne and R.J. Christ, "Ferritization of Ductile Iron", Transactions, American Foundrymen's Society, Vol 74, 1966, pp 371-379.

W. Gruver, "Double Annealing Heat Treatment and it's Effect on the Impact Transition Temperature of Ductile Iron," Private Correspondence, 1968.

K. B. Palmer, "Heat treatment of cast iron – hardening and tempering," BCIRA Journal, November, 1974.

American Society For Metals, Metals Handbook, 9th edition, Vol. 4, Metals Park, OH, 1981.

J.W. Boyes and N. Carter, "Hardenability of nodular cast irons." The British Foundryman, Sept 1966, pp 379-386.

C. C. Reynolds, N. T. Whittington, and H. F. Taylor, "Hardenability of Ductile Cast Iron," Transactions, American Foundrymen's Society, Vol. 63, 1955 pp 116-120.

A. P. Alexander, "Normalized vs. Quenched and Tempered Nodular Iron," Transactions, American Foundrymen's Society, Vol. 81, 1973.

C. R. Isleib and R. E. Savage, "Normalized Alloy Ductile Irons," Transactions, American Foundrymen's Society, Vol. 65, 1957.

A.P. Alexander, "Normalized vs. Quenched and Tempered Iron." Transactions, American Foundrymen's Society, Vol 81, 1973, pp 115-121.

D.R. Askeland and F. Farinez, "Factors Affecting the Formation of Secondary Graphite in Quenched and Tempered Ductile Iron" Transactions, American Foundrymen's Society, Vol 87, 1979, pp 99-106.

K.B. Rundman and T.N. Rouns, "On the Effects of Molybdenum on the Kinetics of the Secondary Graphitization in Quenched and Tempered Ductile Irons.", Transactions, American Foundrymen's Society, Vol 90, 1982, pp 487-497.

J. E. Bevan and W. G. Scholtz, "Effect of Molybdenum on the Transformation Characteristics and Properties of High Strength Ductile Irons," Transactions, American Foundrymen's Society, Vol. 85, 1977.

R. E. Savage, "Heat Treating Ductile Iron," Steel, November, 1955.

M. M. Hallet and P. D. Wing, "Stress Relief Heat treatment of Alloy Cast Iron," Foundry Trade Journal, Vol. 56, 1949.

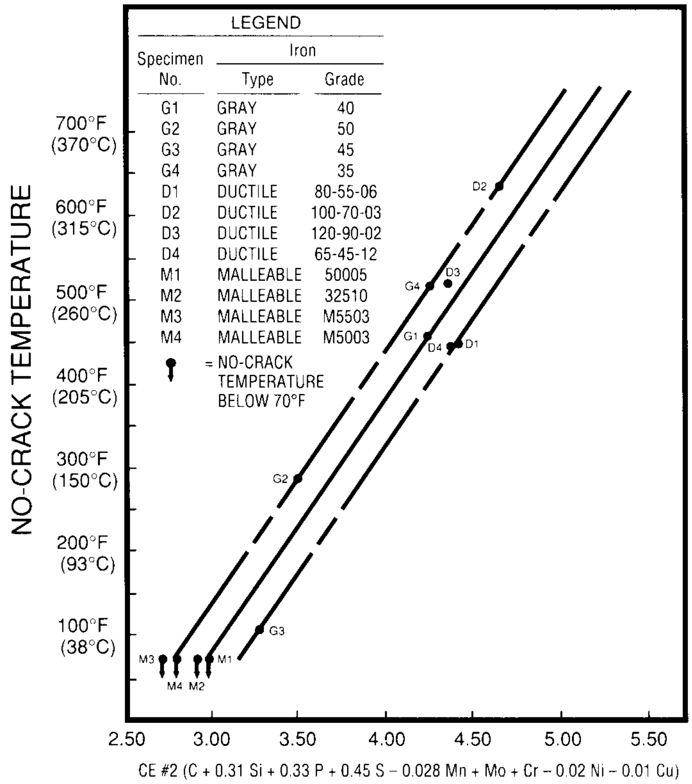
J. H. Schaum, "Stress Relief of Gray Cast Iron," Transactions, American Foundrymen's Society, Vol. 56, 1948.

Back to Table of Contents

SECTION VIII

WELDING
BRAZING
DIFFUSION BONDING
ADHESIVE BONDING

Figure 8.1



Relationship between carbon equivalent and no-crack temperature for cast irons.

Matrix structure	Filler metal	0.2% yield strength, N/mm²	(ksi)	Tensile strength, N/mm²	(ksi)	Elongation, % in 50 mm (2 in.)
Ferritic	Unwelded	232 - 309	(34 - 45)	386 - 541	(56 - 78)	15 - 25
	Nickel 61	304	(44)	422	(61)	11.5
	Monel 60	303	(44)	400	(58)	8.7
	Nilo 55	300	(44)	412	(60)	12.7
Pearlitic	Unwelded	386 - 463	(56 - 67)	618 - 772	(90 - 112)	1 - 3
	Nickel 61	358	(52)	550	(80)	3.5
	Monel 60	346	(50)	495	(72)	2.5
	Nilo 55	339	(49)	425	(62)	5.7

Table 8.1 **Average transverse tensile properties of short-arc MIG-welds between 25 mm (1 inch) thick plates.**

WELDING, BRAZING, DIFFUSION BONDING, ADHESIVE BONDING

Introduction

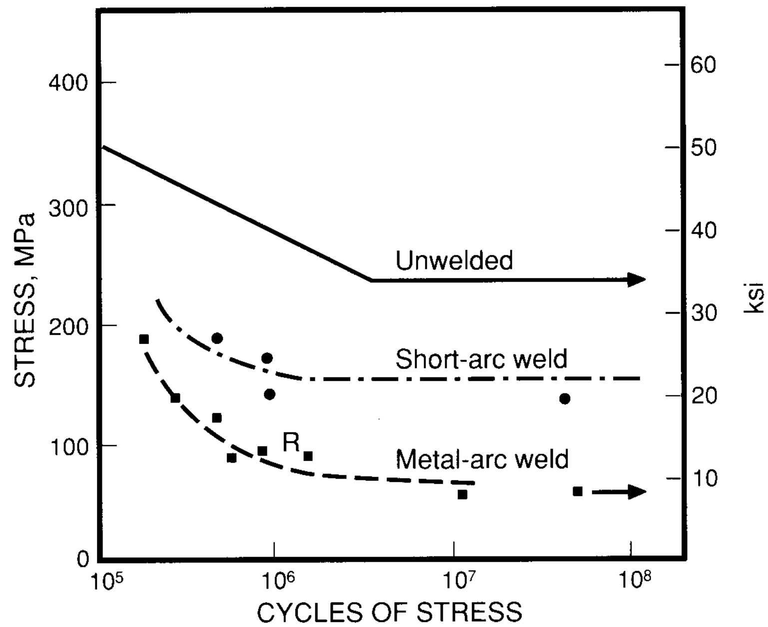
Although the complex shapes produced by the casting process have enabled castings to replace many fabricated components, there are many applications in which, for economic or engineering reasons, castings themselves become part of a fabrication and are joined to other castings or other materials. Although often more cost-effective than steel castings and forgings, Ductile Irons have not been used in some applications requiring joining by welding because they have been considered difficult to weld. This poor weldability of Ductile Iron is partly fact but primarily misconception. When Ductile Iron castings are repaired or joined by fusion welding their high carbon content can cause the formation of carbides in the fusion zone (FZ) and martensite in both the FZ and heat affected zone (HAZ) adjacent to the FZ. The formation of hard brittle phases in the FZ and HAZ can cause a significant deterioration in both machinability and mechanical properties.

Following an investigation into the weldability of various types of cast irons, the American Welding Society Committee on Welding Cast Irons has developed both a weldability test and a set of recommended practices for welding cast irons. The weldability test consists of the production of carefully controlled autogenous welds (an autogenous weld is one made without filler metal) on test castings preheated to various temperatures and the determination of a minimum temperature, called the "no-crack temperature" above which there is no cracking in the test weld. The committee found no correlation between the no-crack temperature and the carbon equivalent (CE) formula used to determine the weldability of steels and the following formula for CE was developed.

$$CE_{CI} = \%C + 0.31\ (\%Si) + 0.33\ (\%P) + 0.45\ (\%S) - 0.028\ (\%Mn + \%Mo + \%Cr) - 0.02\ (\%Ni) - 0.01\ (\%Cu)$$

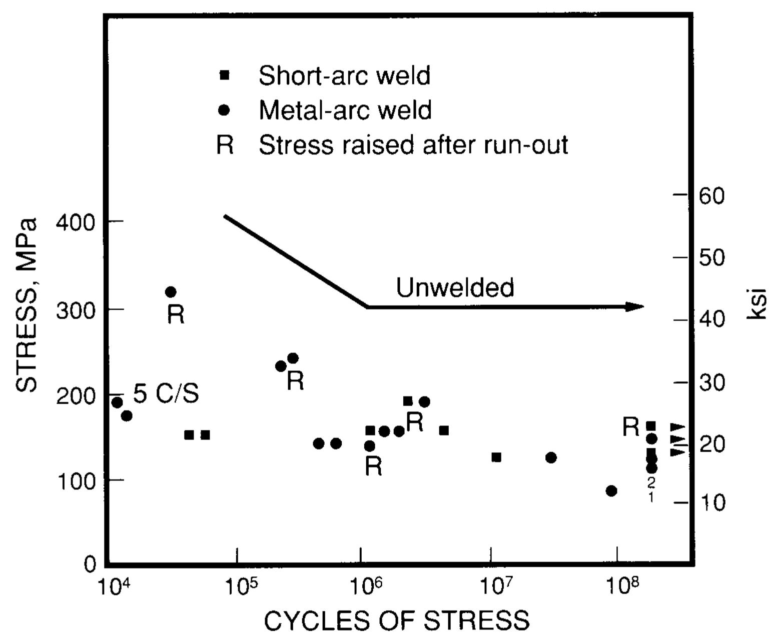
Figure 8.1 shows that there is a good correlation between CE_{CI} and the no-crack temperature for Gray, Ductile and Malleable irons. The autogenous welding method used to obtain this correlation was chosen to simplify and standardize test procedures and is not considered good welding practice for cast irons. For this reason CE_{CI} should be used only to rank weldability rather than determine either absolute weldability or specific preheating conditions. Through the use of welding practices and consumables described in the Guide for Welding Castings and other references used in this Section, Ductile Iron castings have been joined successfully to other Ductile Iron castings and to steel in the fabrication of automotive and other engineering components. In addition, nonfusion joining processes such as brazing, diffusion bonding and adhesive bonding can be used to produce high quality joints between Ductile Iron and a wide variety of other materials.

Figure 8.2



Rotating-bending fatigue strength of welded and unwelded ferritic Ductile Iron.

Figure 8.3



Rotating-bending fatigue strength of welded and unwelded pearlitic Ductile Iron.

WELDING

Welding involves the fusion of both a filler metal (welding consumable) and the base metal adjacent to the weld zone. The high carbon content of Ductile Iron can lead to the formation of carbides in the fusion zone (FZ) and martensite in both the FZ and heat affected zone (HAZ) adjacent to the FZ unless correct procedures are followed. However, with the use of appropriate materials and procedures, Ductile Iron castings can be successfully joined to other Ductile Iron castings and to steel by fusion welding.

ARC WELDING

Several methods have been employed successfully to arc-weld Ductile Iron to itself and other materials with acceptable properties in both the weld and base metal. The properties of shielded metal arc welded Ductile Irons were greatly improved by the introduction over 40 years ago of the high-Ni and Ni-Fe electrodes (AWS Ni-CI and ENi-Fe-CI). These electrodes produce high-nickel fusion zones that are relatively soft and machinable but have adequate tensile strength, ductility and fatigue strength. The short arc, or dip transfer MIG welding process, by virtue of its controlled, low heat input, reduced harmful structural changes in the base metal HAZ. Combining the benefits of Ni-base filler wire with the short-arc MIG process has resulted in welds with tensile properties that are equivalent to the base Ductile Iron (Table 8.1) and fatigue strengths that are 65% and 75% respectively of the fatigue limits of unwelded pearlitic and ferritic Ductile Irons (Figures 8.2 and 8.3). Although suffering from the disadvantages of high consumable costs, low deposit rate (1.8-3.2 kg/h (4-7 lb/h)) and a tendency toward lack-of-fusion defects, short-arc MIG welding has been used successfully for the joining of Ductile Iron castings for commercial applications. Recent work at BCIRA has shown that short-arc MIG welds made with high Ni filler wire have Charpy fracture energies that are superior to those of MIG-welded joints made with Ni-Fe and Ni-Fe-Mn wires and flux-core arc welded joints produced with Ni-Fe wire.

Flux Cored Arc Welding

Flux cored arc welding (FCAW), utilizing a flux cored wire developed specially for the welding of cast irons, has improved upon the metallurgical advantages provided by the Ni-rich consumables and offers the additional advantage of much higher metal deposit rates (6-9 kg/h (13-20 lb/h)). The key to the success of the FCAW process is the consumable, marketed under the trade name "Ni-Rod FC55", which consists of a nickel-iron tubular wire filled with carbon, slagging ingredients, and deoxidizers. In addition to the advantages offered by the high nickel content, Ni-Rod FC55 provides the additional benefits of a high carbon content, which produce graphite precipitates during the solidification of the weld metal. It has been claimed that the expansion resulting from the formation of graphite counteractes weld-metal shrinkage, reducing stress-induced cracking of the weld. The high productivity of the FCAW method, and the good mechanical properties of welded joints (Table 8.2) have resulted in its use in the production of critical, high volume automotive components such as drive shafts, "half-shafts" and wheel spin-

Specimen	Shielding	0.2% offset yield strength, N/mm² (ksi)		Tensile strength, N/mm² (ksi)		Elongation %	Reduction of area %	Hardness, HRB
All-weld-metal	None	310	(45)	476	(69)	15.5	14.5	81
All-weld-metal	CO_2	314	(45)	496	(72)	21.0	18.8	80
All-weld-metal	Sub-arc flux	338	(49)	510	(74)	18.5	20.6	86
Transverse	None	300	(44)	455	(66)	–	–	–
Transverse	CO_2	303	(44)	455	(66)	–	–	–
Transverse	Sub-arc flux	310	(45)	441	(64)	–	–	–
All-weld-metal*	CO_2	303	(44)	468	(68)	15.0	16.2	80
Transverse*	CO_2	300	(44)	467	(68)	–	–	–

*Pulsing-arc power source.

Table 8.2 **Mechanical properties of joints welded with flux-cored wire Ni-Rod FC55: base material ASTM grade 60/45/10 Ductile Iron.**

Matrix structure	Welding* process	Protective gas	Yield strength N/mm²	(ksi)	Tensile strength, N/mm²	(ksi)	Elongation %	Reduction in area %
Ferritic	Unwelded	–	323	(47)	481	(70)	13	14.7
	MIG	Argon	366	(53)	445	(65)	2.3	10.7
		Argon 2% O_2	387	(56)	482	(70)	5.0	20.5
		Stargon†	385	(56)	455	(66)	2.3	5.6
		75% Ar – 25% CO_2	397	(58)	493	(72)	3.0	8.5
		CO_2	390	(56)	499	(72)	2.7	14.0
	SAW	–	341	(49)	498	(72)	6.0	8.2
	TIG	Argon	392	(57)	507	(74)	5.0	19.5
	MMA	–	365	(53)	490	(71)	8.3	15.3
Pearlitic	Unwelded	–	413	(60)	693	(100)	6	4.7
	TIG	Argon	503	(73)	629	(91)	1.5	3.2
	MMA	–	447	(65)	580	(84)	3.0	1.6

*MIG: metal inert gas
*SAW: submerged arc welding
TIG: tungsten inert gas
MMA: manual metal arc
†Trademark of Linde (Union Carbide).

Table 8.3 **Properties of welds made between 19 mm (0.7 in.) thick Ductile Iron plates using a 44%Fe-44%Ni-11%Mn filler wire.**

dles on off-road vehicles. This ability to economically produce high quality welds has given foundries the added freedom to employ cast-weld techniques for the production of complex components.

Recently a nickel-iron-manganese alloy, "Ni-Rod 44", with a nominal composition of 44% Fe, 44% Ni and 11% Mn was developed to further reduce the risk of cracking in the HAZ. Available as both filler wire and manual electrodes, Ni-Rod 44 has been evaluated using various welding procedures on both ferritic and pearlitic Ductile Irons. Table 8.3 shows that Ni-Rod 44 welded joints have good strengths but lower ductility, compared to MIG-welded joints produced with a high-nickel consumable.

Gas Welding

Gas welding can be used to join Ductile Iron components by the creation of either fusion or diffusion bonds. Gas fusion welding is a well established welding method for joining Ductile Iron. The process simply involves fusion of the base metal and filler rod by heat generated from an oxy-acetylene flame. The weld pool is constantly being fluxed. When Ductile Iron filler rods are used and fluxes of suitable composition (usually incorporating cerium and/or other rare earth elements) are used the weld deposit solidifies like a Ductile Iron, with the formation of graphite spheroids. Successful gas fusion welding depends upon controlled preheating of the workpiece, maintenance of a controlled and well fluxed weld pool and the use of suitable consumables. The major disadvantages of this process are low productivity, dependence on operator skill and the distortion of complex castings by excessive heat input. However, when correct procedures and materials are employed, gas fusion welding can produce joints with strength and ductility properties comparable to the base metal.

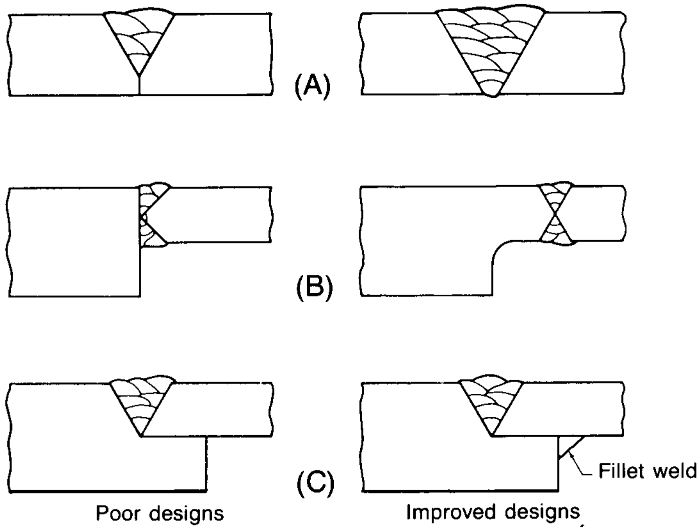
Powder Welding

Powder welding is a non-fusion form of gas welding in which a modified oxyacetylene torch serves as both a powder supply and heat source. The melting point of the deposited powder is below that of the base iron and when the base iron surface reaches a certain temperature, the deposited powder coating melts and "wets" the casting surface. Subsequently the weld is built up as the preheated powdered alloy continuously melts as it impinges on the wetted surface. Powder welding does not fuse the base iron and the success of the weld is determined by the development of a diffusion bond. Powder welding has several limitations. It is slow, expensive and is restricted to horizontal welding. Although the casting is not heated to its melting point, sufficient heat may be applied to cause distortion in complex castings. Powder welding is used for defect repair, cladding and joining high alloy irons. Work at BCIRA has shown some promise for the joining of ferritic and pearlitic Ductile Irons.

Significant Welding Variables

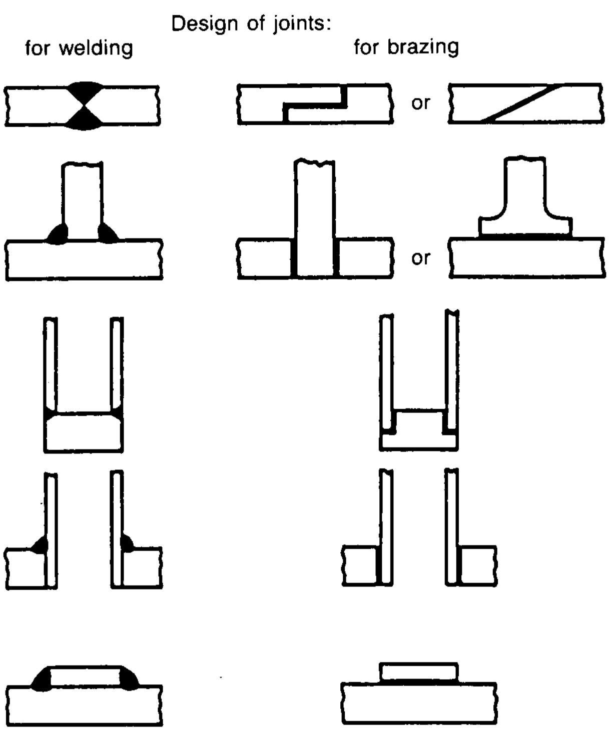
Selection of the correct welding procedure and consumable is a necessary but not sufficient condition for the production of high quality welds in Ductile Iron. Other critical variables are:

Figure 8.4



Joint design improvements.

Figure 8.5



Joint designs for welding and brazing.

- type and composition of the base Ductile Iron,
- design and preparation of the welded joint, and
- control of the thermal history of the component before, during and after welding.

Iron Type and Composition

Although the cast iron weldability test indicates that the ''no-crack temperature'' is related to composition but not microstructure (Figure 8.1), ferritic Ductile Irons are generally considered to have the highest weldability of all grades of Ductile Iron. Composition influences weldability primarily through CE_{CI} – the higher CE_{CI} is, the more susceptible the casting is to cracking. Composition also affects weldability through its influence on the hardenability of the HAZ. Manganese and chromium strongly increase hardenability, which reduces weldability through the increased tendency to form martensite in the HAZ. Although silicon increases hardenability slightly, this effect on weldability is offset by the strong graphitizing effect of silicon, which improves weldability by reducing carbide formation.

Joint Design and Preparation

The design of a welded joint is dependent upon factors such as metal thickness, casting geometry, welding process and service requirements. Whenever possible, the design should ensure that the components being joined, rather than the weld, carry most of the load. With a welded assembly the designer can often position the weld in an area of low stress. Figure 8.4 provides examples of joint designs which have been improved to reduce joint stress and increase weld penetration, while Figure 8.5 illustrates recommended joint designs for both welding and brazing. To ensure sound, gas-free welds, the casting skin adjacent to the joint should be removed and the joint surfaces should be freshly ground or machined and any scale, rust, dirt, grease and oil removed.

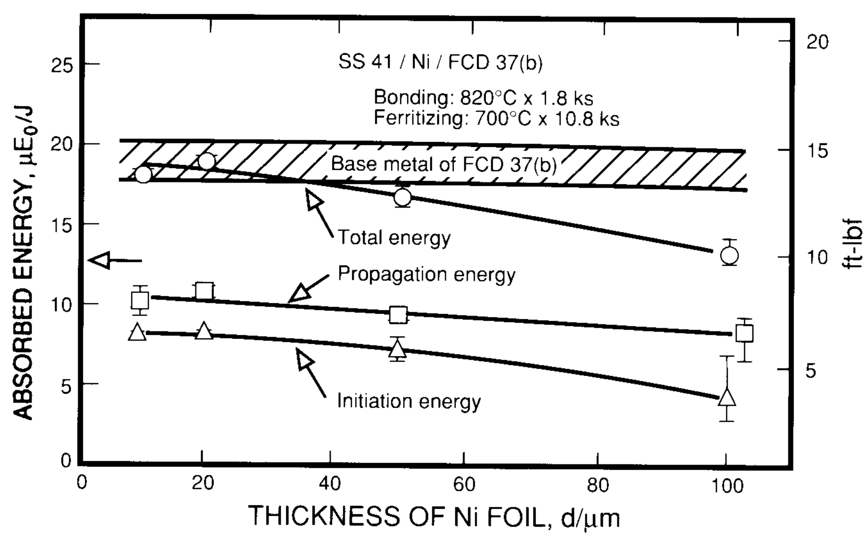
Thermal Treatments

When practical, the casting should be preheated in order to prevent thermal cracking, reduce hardness in the HAZ and reduce residual stresses and distortion. It is preferable that the entire casting be preheated but when casting size or the lack of facilities makes this impractical, castings can be preheated with burners or an oxy-acetylene torch. When local preheating methods are employed, extreme care is required to avoid rapid, non-uniform heating to avoid cracking and distortion in complex castings. Ferritic Ductile Irons require only a mild preheating in the range 300-400°F (150-200°C). Pearlitic Ductile Iron requires higher preheating temperatures, 600-650°F (315-340°C). Low heat input welding methods such as short-arc MIG minimize the harmful effects of the HAZ. Post-weld thermal treatments such as slow cooling and postheating may be required to reduce residual stresses. Depending upon service requirements, the welded assembly may be subjected to annealing or normalizing heat treatments to dissolve carbides and produce the desired mechanical properties.

Characteristics	Process				
	Soldering	Brazing		Bronze-welding (or braze welding)	Powder-welding
		Low-temperature	High-temperature		
Melting-point or melting-range of filler-metal	<450°C (840°F)	400 - 1000°C (750 - 1830°F)	≃ 1000°C (≃1800°F)	Not specified	Not specified
Typical filler-metal-alloys	Pb-based Zn-based	Ag-based Cu-based	Ni-based Au-based Pd-based	Cu-based (usually Cu-Zn)	Ni-based Cu-based
Joint type	Capillary	Capillary	Capillary	Large gap or external fillet	Large gap or external fillet

Table 8.4 **Non fusion joining processes.**

Figure 8.6



Charpy impact energy of diffusion-bended joint between ferritic Ductile Iron and carbon steel.

BRAZING

The formation of less than optimum microstructures in both the FZ and HAZ during the fusion welding of Ductile Irons makes non-fusion joining techniques attractive alternatives. Brazing is "the joining metals by the fusion of non-ferrous alloys that have melting points above 800°F (425°C) but lower than those of the metals being joined". During the brazing process the melted filler metal flows by capillary action into a narrow gap between the components and solidifies to form a bond. Brazing is related to soldering, braze-welding, and powder-welding, but is distinguished from these processes either by the type and melting range of the filler metal or by the design of the joint (Table 8.4).

Joint Design and Preparation

Unlike welded joints, the joint-gap for brazing (Figure 8.5) is narrow and of controlled thickness to maximize joint strength, induce penetration of the brazing alloy by capillary flow, and reduce the amount of brazing alloy consumed. The joints should preferably be designed to operate in compression or shear. Although brazed joints can have excellent mechanical properties under pure tensile loading, any bending moment will severely reduce the mechanical properties. Ductile Iron should be prepared for brazing by removal of the casting skin, roughening of the surface with an abrasive, degraphitization of the joint surfaces with an oxidizing oxy- acetylene flame or a salt bath and degreasing and cleaning with a suitable solvent.

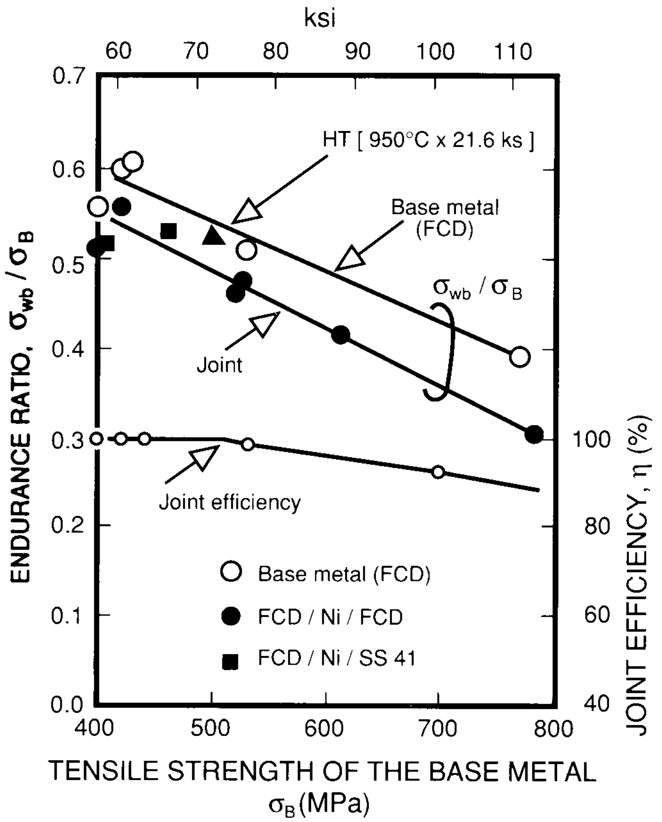
Heating

The choice of a heating method for brazing depends on the component size, joint design, brazing alloy, and production rate. Brazing Torches can be hand operated, which is flexible but requires considerable operator skill, or used as fixed heat sources in a mechanized brazing line. Induction brazing is a rapid and reproducible heating method generally used on long production runs. Batch or continuous furnaces are frequently used when the entire component is heated to the brazing temperature. Brazing furnaces may have inert or reducing atmospheres or a vacuum to prevent oxide formation on both the workpiece and brazing alloy, or an air atmosphere may be used, in which case a brazing flux is required.

Diffusion Bonding

Diffusion bonding, in which both similar and dissimilar metals can be joined by solid state diffusion processes, can be used to overcome the microstructural problems related to fusion welding while providing a joint that is significantly stronger than that produced by other non-fusion processes. The use of a Ni foil varying in thickness from 10-100 um (0.0004-0.004 in.), with bonding temperatures and times of 820°C (1510°F) and 30 minutes has resulted in bonds between Ductile Iron and carbon steels with exceptional mechanical properties. These bonds have impact properties and endurance ratios equal to the base Ductile Iron (Figures 8.6 and 8.7) and a joint efficiency (ratio of the tensile strength of the joint to that of the base metal) which decreases from 98% to 92% as the strength of the Ductile Iron increases from 400 MPa (58 ksi) to 700 MPa (100 ksi).

Figure 8.7



Endurance ratios and joint efficiencies for diffusion-bonded joints between various grades of Ductile Iron and carbon steel.

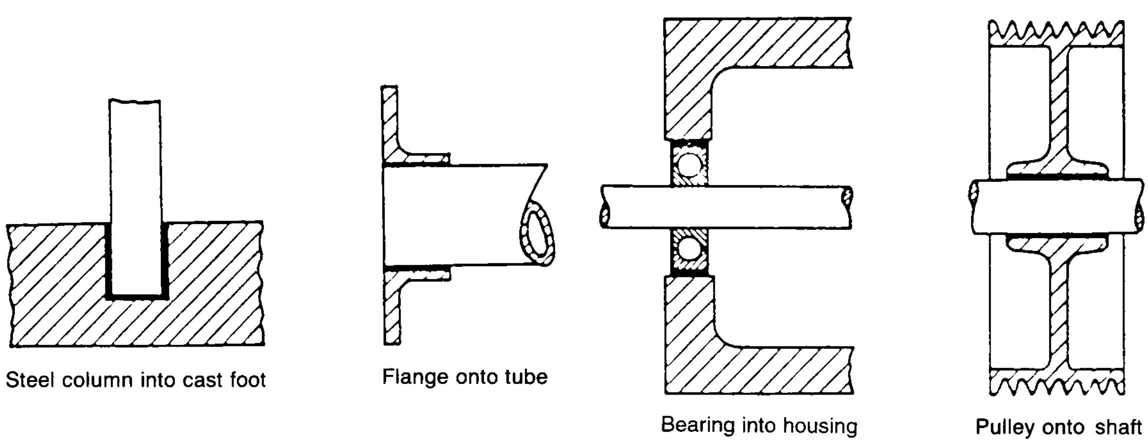


Figure 8.8 **Examples of adhesive joint design.**

Adhesive Bonding

Adhesive bonding is being used increasingly for the joining of engineering materials, especially sheet metals. In addition to the elimination of structural changes in the base metal, the absence of heat input in adhesive bonding also eliminates the problem of distortion and permits the bonding of Ductile Iron to a wide variety of metallic and non-metallic materials, regardless of their melting points or physico-chemical properties. The most common adhesives used in structural metal-to-metal bonds are: anaerobics, toughened acrylics and epoxy resins. Adhesive bond strengths are significantly lower than the strength of ferritic Ductile Iron and as a result, careful consideration must be given to joint design in applications in which strength is a requirement. Figure 8.8 illustrates typical examples of adhesive joints. Enhanced joint performance can be obtained through specialized joint designs which convert tensile and shear stresses into compressive stresses. Other limitations to the use of adhesive joints are their limited operational temperature range and a general lack of data on the performance of adhesive bonding in long term applications involving different loading and environmental conditions.

REFERENCES

Guide for Welding Iron Castings, American Welding Society, 1989, 550 N. W. Lejeune Road, P.O. Box 351040, Miami Florida 33135. "Arc Welding of Cast Irons." Metals Handbook, Volume 6, 9th Edition, American Society for Metals, Metals Park, Ohio 44073.

S. I. Karsay, Ductile Iron II, Quebec Iron and Titanium Corporation, 1972.

R. D. Forest, "Welding Ductile Iron Castings," Casting Engineering and Foundry World, Spring, 1983.

D. G. Howden, "Designs for Effective Welding," Machine Design, May 25, 1989.

I. S. Matharu and K. Selby, "The Charpy v-notch and tensile properties of a ferritic ductile iron welded using MIG and FCAW methods." BCIRA Research and cast metals practice, July 1990, pp 195-201.

J. L. Osman, N. Stephenson, and D. R. Thorneycroft, "Developments in the Welding of S. G. Iron," The Ductile Iron Bulletin, November, 1963.

H. L. Morgan, "Joining of iron Castings," Proceedings of the BCIRA Conference on engineering properties and performance of modern iron castings, Loughborough, England, April, 1970.

R. A. Harding, "Progress in joining iron castings," British Foundrymen, November, 1987 pp 444-455.

J. L. Osman and N. Stephenson, "Further aspects of the welding of SG iron," Institute of Welding and British Welding Research Association, Second Commonwealth Welding Conference, London, England, 1966.

R. C. Voigt and C. R. Loper, "Welding Metallurgy of Gray and Ductile Cast Irons," Transactions, American Foundrymen's Society, Vol. 94, 1986.

R. A. Bishel, "Flux -cored electrode for cast iron welding," Welding Journal, June, 1973.

R. A. Bishel, and H. R. Conaway, "Flux-cored Arc Welding for High- quality Joints in Ductile Iron," Transactions, American Foundrymen's Society, Vol. 84, 1976.

S. D. Kiser, "Production Welding of Cast Irons.", Transactions, American Foundrymen's Society, Vol 85, 1977, pp 37-42.

M. A. Davila, D. L. Olson and T. A. Freese, "Submerged Arc Welding of Ductile Iron.", Transactions, American Foundrymen's Society, Vol 85, 1977, pp 79-86.

T. J. Kelly, R. A. Bishel, and R. K. Wilson, "Welding of Ductile Iron with Ni-Fe-Mn filler metal," Welding Journal, March, 1985.

R. Medana, E. Natale, M. S. Remondino, "High Strength Welding of Ductile Iron Castings." Transactions, American Foundrymen's Society, Vol 86, 1978, pp 611-616.

The Iron Castings Handbook, Iron Castings Society, Inc., 1981.

E. N. Gregory and S. B. Jones, "Welding Cast Irons," Proceedings, International Conference on Welding, the Welding Institute, Cambridge, England, 1977.

K. Nishio, M. Katoh and S. Mukae, "Fatigue Strengths of Diffusion Bonds of Spheroidal Graphite Cast Irons." Transactions, Japan Welding Society, Vol 19, April 1988, pp 17-27.

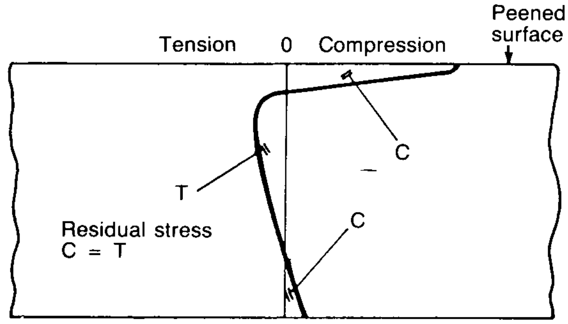
S. Mukae, K. Nishio, M. Katoh and N. Nakamura, "Impact Characteristics of Diffusion Bonds of Ferritic Spheroidal Graphite Cast Iron." Transactions, Japan Welding Society, Vol 21, April 1990, pp 41-51.

Back to Table of Contents

SECTION IX

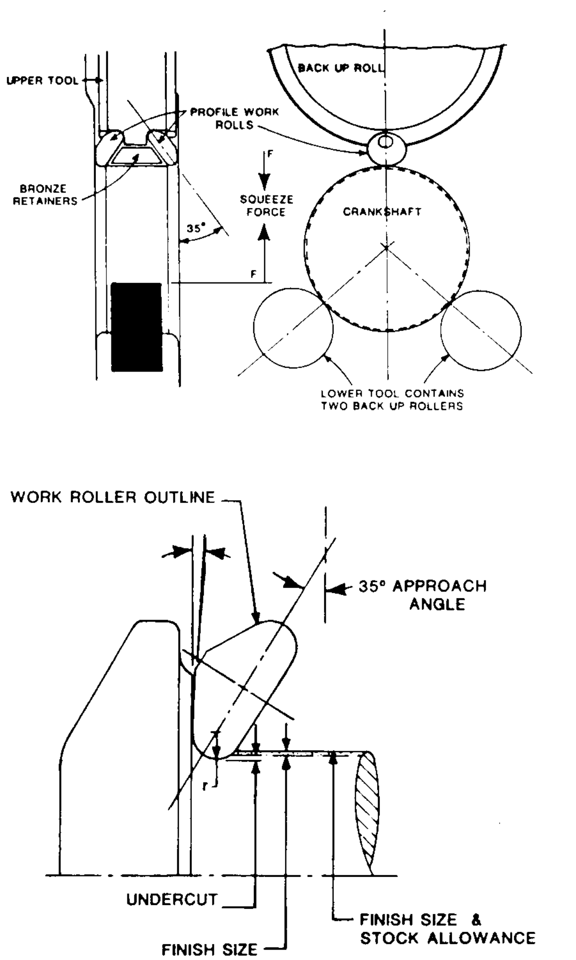
SURFACE TREATMENT

Figure 9.1



Distribution of stress in a shot-peened beam with no external load.

Figure 9.2



Schematic diagrams of tooling for undercut deep-fillet rolling of Ductile Iron crankshafts.

SURFACE TREATMENT

Introduction

Surface treatments are applied to castings for engineering, aesthetic and economic reasons. The surfaces of industrial castings may be treated to provide improved surface-related properties such as wear, fatigue and corrosion resistance. In castings used in consumer products, improved appearance is also an important objective of surface treatments. In many cases, surface treatment permits a casting to meet mutually exclusive design objectives. For example, the application of an abrasion-resistant coating will enable a Ductile Iron casting to be both wear resistant, a surface property, and impact resistant, a bulk property. However, regardless of the engineering and aesthetic objectives, the main reason for using surface-treated Ductile Iron castings is that they offer the most cost-effective means of meeting these objectives. Surface treatments commonly applied to Ductile Iron castings include: thermal and mechanical hardening treatments: the application of fused coatings to reduce friction and improve wear and corrosion resistance; the use of hot dipped metal coatings to improve appearance and corrosion resistance: the electrodeposition of metal coatings to increase corrosion and wear resistance and improve appearance and the application of diffusion coatings to increase resistance to wear, oxidation, and corrosion.

THERMAL-MECHANICAL SURFACE HARDENING

Thermal surface hardening is a common and highly cost-effective method of improving the wear and fatigue resistance of Ductile Iron castings. Thermal hardening involves the rapid heating of the surface layer of a casting to produce a high carbon austenite which, upon removal of the heat source, is cooled sufficiently rapidly, either by self-quenching or the application of a quenching medium, to produce a martensitic structure. In addition to significantly increasing hardness, the formation of martensite creates compressive stresses in the surface layer, impeding the formation and propagation of cracks. Although slightly softer than hardened steel, the combination of a martensitic matrix and graphite nodules in surface hardened Ductile Iron can produce superior resistance to sliding wear. Flame, induction, and laser hardening are the most common methods used to thermally surface harden Ductile Iron castings.

Shot-Peening

Shot-peening hardens the surface of a Ductile Iron casting by the controlled impingement of spherical particles of hardened steel, ceramic or glass. This impingement produces a deformed, compressively stressed surface layer (Figure 9.1) having a depth and degree of stress that are controlled by peening parameters such as shot size and hardness, speed and angle of impingement and exposure time. For consistency of depth and hardness, shot peening should be mechanized and "Almen Strips" used to measure peening intensity. Shot-peening can significantly increase fatigue strength in both conventional (Figure 3.34) and austempered Ductile Irons (ADI) (Figures 4.17, 4.18, 4.35 and 4.36). Shot-peening is especially effective in improving the performance of ADI

Surfacing Materials	Classes	Application Methods	General Properties	Typical Uses
Ferrous Alloys, hardenable & austenitic	EFe, RFe5, ECI, RCI, EFeCr, RFeCr, EFeMn	Arc or Gas Welding	Hardenability increases with increase in carbon content. Austenitic types are hardenable by cold working.	Intermediate face for subsequent hard facing crushing equipment and abrasive applications. Metal to metal wear.
Cobalt Base	ECoCr, RCoCr	Arc or Gas Brazing	Corrosion and abrasion resistant. Hardness lower than ferrous alloys, but retained at elevated temperatures.	Valves and seats of internal combustion engines. Hot-working die facing and repair.
Carbides	WC, W_2C	Arc or Gas Welding	Maximum hardness and abrasion resistance. Brittleness dependent on matrix and backup metal.	Cutting and chopping of minerals and metals. Severely abrasive applications.
Copper Base	ECuZn, RCuZn, ECuSn, RCuSn, ECuAI, RCuAI	Arc or Gas Brazing	Corrosion resistant. Good antifriction properties. Excellent electrical conductivity.	Friction bearing surfaces. Moderate hardness for inlays on gear teeth.
Nickel Base	ENiCr, RNiCr	Arc or Gas Welding. Spraying	Heat and corrosion resistant. Fair hardness and impact resistance retained at elevated temperatures.	Hot gas and corrosion service. Suitable for hot-working surfaces that are to be machined.

Table 9.1 **Fusion coating materials, their properties and uses.**

Coating	Hardness	Elec. Res. Microhm-centimetre	Abrasion Resistance	Appearance		Thickness Mils	*Micrometres*	Characteristics and Uses
Aluminum	30-90 Vickers	2.8	Poor	White		0.25	*6.4*	Good thermal and heat resistance properties when diffused into base iron.
Cadmium	30-50 Vickers	7.5	Fair	Bright White		0.15-0.5	*3.8-12.7*	Pleasing appearance for indoor applications. Less likely to darken than zinc.
Chromium	900-1100 Vickers	14-66	Excellent	White - can be varied	(decorative) (hard)	0.01-0.06 0.05-12.0	*0.3-1.5* *1.3-304.8*	Excellent resistance to wear abrasion and corrosion. Low friction and high reflectance.
Cobalt	250-300 Knoop	7	Good	Gray		0.1-1.0	*2.5-25.4*	High hardness and reflectance.
Copper	41-220 Vickers	3-8	Poor	Bright Pink		0.2-2.0	*5.1-50.8*	High electrical and thermal conductivities. Used as undercoat for other electroplates.
Lead	5 BHN	10	Poor	Gray	(wear) (corrosion)	0.5-8.0 50	*12.7-203.2* *1270*	Resistant to many acids, hot corrosive gases, and atmospheres.
Nickel	140-500 Vickers	7.4-10.8	Good	White	(decorative) (wear)	0.1-1.5 5-20	*2.5-38.1* *127-508*	Resistant to a variety of chemicals and corrosive atmospheres. Used as undercoat for chromium.
Rhodium	400-800 BHN	4.7	Good	Bright White		0.001-1.00	*0.025-25.4*	High electrical conductance. Brilliant white appearance is tarnish and corrosion resistant.
Tin	5 BHN	11.5	Poor	Bright White		0.015-0.5	*0.38-12.7*	Corrosion resistant. Hygienic applications for good and dairy equipment.
Zinc	40-50 BHN	5.8	Poor	Matte Gray	(decorative) (corrosion)	0.1-0.5 0.5-2.0	*2.5-12.7* *12.7-50.8*	Easily applied. High corrosion resistance.

Table 9.2 **Electroplated coatings, their properties, characteristics and uses.**

because the resultant deformation transforms the stabilized austenite into martensite, producing both hardening and compressive stresses. In addition to increasing wear resistance and fatigue strength, shot-peening is also used to retard stress-corrosion cracking, relieve internal stresses, correct distortion and prepare surfaces for coating.

Surface Rolling

Surface rolling, like shot-peening, hardens the casting surface by the introduction of controlled deformation such as that exemplified by the fillet rolling of crankshafts (Figure 9.2). Like shot-peening, surface rolling can produce significant increases in the fatigue strength of conventional Ductile Iron and ADI components, especially those having unavoidable stress concentrations (Figure 3.35 and Table 3.3).

SURFACE COATING

Fusion Coatings

Fusion coatings can be applied with any of the fusion welding processes used to repair and join Ductile Iron castings (see Section VIII) and also by flame, arc and plasma spraying processes. Table 9.1 summarizes the surfacing processes, properties and typical uses of the five major classes of fusion coating materials.

Electroplated Coatings

Electroplated coatings are frequently applied to Ductile Iron castings to provide special surface properties such as resistance to corrosion, wear and abrasion, special surface colour and reflectivity, and good general appearance. For some applications ductility and solderability are also important coating characteristics. Table 9.2 describes conventional electroplated coatings, their properties and typical uses.

Hot-Dipped Coatings

Hot-dip coatings are usually thicker than other coatings and are bonded firmly to the casting by a thin diffusion layer between the coating and casting. Table 9.3 lists the most common hot-dipped coatings, their structures and uses. The widely used process of hot-dip galvanizing produces the heaviest and most durable protective coating for iron castings. The substantial, uniform, and adherent coating of zinc provides effective protection against corrosion by acting as a barrier film against environmental corrosive attack and by sacrificial corrosion. Precautions should be taken to avoid the embrittlement of annealed ferritic castings by the galvanizing process (see page 3-55).

Diffusion Coatings

Diffusion coatings are applied by holding the castings at high temperature in intimate contact with the coating agent, which can be in one of four forms: powdered metal, volatilized metal or metallic salt, fused metal salts, or a gaseous atmosphere. The resultant diffusion processes alloy the surface layer of the casting to produce the desired mechanical and chemical properties. In diffusion coating the ''coating'' is not visible and is an integral part of the surface microstructure of the casting. Figure 9.4 lists the different types of diffusion coatings and describes their properties and uses. Figure 3.36 illustrates the significant increase in fatigue strength produced by the nitriding of a Ductile Iron casting.

Type	Coating Structure	Thickness or Weight	Uses
Galvanizing	Outer layer of zinc over a base layer of an iron-zinc compound.	2 to 8 ounces per square foot *9 to 35 g/cm²*	Atmospheric corrosion resistance where non-staining corrosion products are desirable.
Tinning	Tin surface layer over an intermetallic tin-iron phase.	0.3 to 1.5 mils *7.6 to 38.1 μm*	Resistant to tarnishing in food service and non-industrial atmospheres. Intermetallic bond for bearings. Metallurgical bond for soldering.
Lead and Lead Tin	Mechanical bond of outer layer to substrate.	0.2 to 0.6 mils *5.1 to 15.2 μm*	High resistance to industrial atmospheric corrosion. Chemical process applications, especially with sulphuric and hydrochloric acids.
Aluminizing	Aluminum outer layer over an interfacial iron-aluminum layer.	2 to 4 mils *50.1 to 101.6 μm*	Corrosion and heat application up to 1000°F (540°C). Minimizes high temperature oxidation.

Table 9.3 Summary of hot-dipped coatings, their structures and uses.

Type	Coating Structure	Properties	Uses
Calorized	Metallic aluminum introduced into surface layer forming aluminum-iron alloy.	High temperature oxidation resistance.	Chemical process equipment, steam superheaters.
Chromized	Chromium carbide case formed on surface.	High hardness and wear resistance.	Combustion and mechanical equipment.
Cyanided Carbonitrided	Carbon-nitrogen compound formed by diffusion into surface.	Wear and thermal fatigue resistance.	Gears, cams, pawls, and engine heads.
Nickel-Phosphorous	Ammonium phosphate and nickel oxide products reduced and diffused.	Corrosion resistance comparable to austenitic irons. Poor wear resistance.	Chemical process pipe and fittings.
Nitrided	Nitrogen introduced into surface by contact of ammonia or other nitrogenous material.	Wear and corrosion resistance at elevated temperatures.	Same as for carbonitrided.
Sheradized	Zinc introduced into surface.	Corrosion resistance.	Atmospheric corrosion resistance.

Table 9.4 Types of diffusion coatings, their characteristics and uses.

REFERENCES

The Iron Castings Handbook, Iron Castings Society, Inc., 1981.

S. I. Karsay, Ductile Iron II, Quebec Iron and Titanium Corporation, 1972.

BCIRA Broadsheet 281, "Introduction to surface treatments," British Cast Iron Research Association, 1984.

Metals Handbook, "Heat Treating of Ductile Irons," American Society for Metals, Vol. 4, 9th edition, 1981.

Back to Table of Contents

SECTION X

DESIGNING WITH DUCTILE IRON

COMPONENT	CONVERTED FROM	CONVERTED TO	COST SAVING	OTHER DESIGN IMPROVEMENTS
Off-road Truck Suspension Cylinder	Welded Steel Fabrication	BS2789 420/12	>20%	Reduced machining costs. Reduced inventory and stock control costs.
Backhoe Loader Stabilizer Foot	Steel Weldment	ASTM A-536 80-55-06	49%	Used as-cast. All machining and fabricating costs eliminated.
Rope Clamp and Eye Nut	Steel Forging	ASTM A-536 80-55-06	82%	Stronger. Improved appearance.
Crankshaft for Supercharged Engine	Steel Forging	ASTM A-897 ADI	39%	Lighter/stronger/improved wear resistance. Improved sound dampening.
Diesel Engine Timing Gears	Carburized Steel Forging	ASTM A-897 ADI	30%	Increased machine shop productivity. Reduced wt. & noise. Rapid "break-in".
Aircraft Towbar Head	Steel Weldment	ASTM A-536 80-55-06	76%	Improved mech. properties. Reduced machining. Improved appearance.
Worm Gear and Post Screw	Bronze & Steel Fabrication	ASTM A-536 60-40-18	46%	Improved performance. Simplified final assembly.
4WD ATV Wheel Hub	Aluminum Casting	ASTM A-536 65-45-12	50%	Light weight. Increased strength and safety. Improved aesthetics.
Fertilizer Injection Knife	Steel Forging and Weldment	ASTM A-897 ADI	44%	Excellent wear resistance. Eliminated all fabrication costs.
Stainless Steel Banding Jig	Tool Steel Inv. Casting	ASTM A-897 ADI	77%	Significant reduction in machining costs achieved with equal performance.
Wire Rope Clamp	Steel Forging	ASTM A-536 80-55-06	92%	Close tolerance as-cast. High strength. Marketing advantages.
Aircraft Door Fixture	Steel Weldment	ASTM A-536 65-45-12	78%	Solved warpage problem. Increased strength. Reduced number of parts.
Gas Turbine Casing	Steel Castings	BS2789 420/12	>30%	Additional savings in machining costs. 17% less wt. Better vibration damping.
Truck Drive Shaft U-Joint Slip Yoke	Steel Forging	ASTM A-536 100-70-03	47%	Reduced material and machining costs for equivalent reliability.
Tractor Brake Anchor	Steel Fabrication	ASTM A-536 80-55-06	44%	Equivalent mechanical properties with reduced machining costs.
Air Compressor Block	Steel Weldment	ASTM A-536 65-45-12	46%	Improved sound damping and product integrity. Reduced mfg. operations.
Automobile Steering Knuckle	Eleven-part Assembly	ASTM A-536 60-40-18	large	Reduced mfg. operations, parts inventory. Improved reliability.
Photometer Housing	Steel Fabrication	ASTM A-536 65-45-12	45%	Weight reduction. Improved appearance. Improved performance.
Truck Cab Mount	Steel Fabrication	ASTM A-536 80-55-06	31%	Improved fatigue life. 2 castings replaced 34 parts and 25 welds.
Cam for Cotton Picker	Hardened Tool Steel	SAE J-434C D5506	68%	Reduced surface loads. Increased picking speeds. Improved efficiency.
Backhoe Loader Swing Pivot	Steel Weldment	ASTM A-536 65-45-12	31%	Reduced mfg. time. Better machining Improved wear properties.
Tractor Transmission Hydraulic Lift Case	Gray Iron Casting	BS2789 420/12	40% vs Steel	Uprated design req'd stronger material. Steel casting 40% more + pattern change
Plug Valve	SS, Monel and Titanium	ASTM A-536 60-40-18	66%	Close dimensional tolerances. Enabled installation of plastic liner.
Air Compressor Crankcase	Steel Weldment	ASTM A-536 60-40-18	82%	Improved sound damping and shock resistance.

Table 10.1 **Examples of conversions to Ductile Iron.**

DESIGNING WITH DUCTILE IRON

Introduction

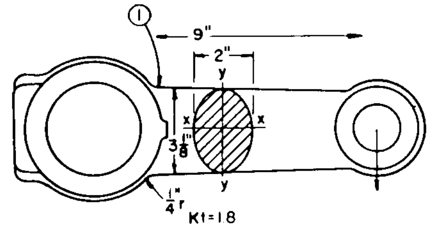
In the past 40 years the use of Ductile Iron has grown rapidly, mainly through conversions from Gray and Malleable Iron castings and steel-castings, forgings and fabrications but also through its use in new components designed with Ductile Iron. Ductile Iron has been successful because it has offered the design engineer a combination of versatility and properties not available in any of its rivals. Its castability, machinability, damping properties, and economy of production are almost equal to those for which Gray Iron is famous, but its mechanical properties – strength, wear resistance, fatigue strength, toughness and ductility – are competitive with many cast, forged and fabricated steel components. The conversion of Gray Iron castings to higher strength Ductile Iron has given the designer two alternative routes to improved component value: significant weight reduction with improved performance through redesign, or lesser but still substantial improvements in performance while maintaining the significant production and commercial benefits of keeping the existing design. Conversions from steel have offered similar, methods of improving cost effectiveness: new designs to improve performance and manufacturability, or the use of existing designs to provide equivalent performance, improved manufacturability and a 10 per cent reduction in weight. In summary, Ductile Iron has been successful because it has offered the designer superior value – higher quality and performance at lower cost.

The driving force of superior product value is clearly evident in the examples in Table 10.1 of successful designs involving conversions to Ductile Iron castings. These examples, taken from Designs in Ductile Iron and Ductile Iron Castings show that, in addition to improvements in product quality, performance and reliability, the replacement of other materials by Ductile Iron castings is also driven by substantial cost savings gained through lower casting cost and superior manufacturability. The numerous design improvements in this Table, subdivided according to their roles in the product value equation, follow.

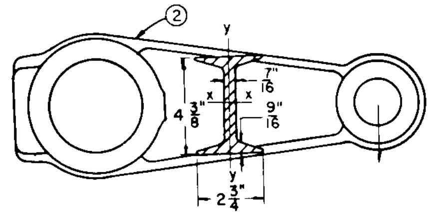
Product Performance/Quality	**Manufacturability**
Increased strength & safety	Often used as-cast
Higher strength/weight	Reduced machining tolerances
Improved wear resistance	Reduced machining costs
Improved sound damping	Reduced number of parts
Reduced weight	Reduced/eliminated welds
Improved fatigue life	Reduced inventory costs
Uprated performance	Reduced mfg time/costs
Improved shock resistance	Solved warpage problem
Improved integrity/reliability	Increased productivity
Improved appearance	Simplified assembly
Marketing advantages	Reduced material costs

Many of these advantages have been discussed in the preceding Sections, which have addressed both fitness for purpose and manufactura-

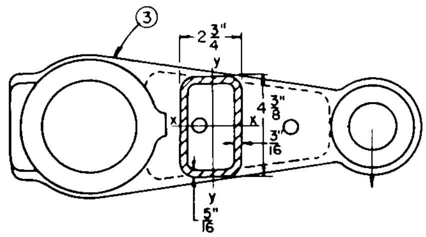
Figure 10.1



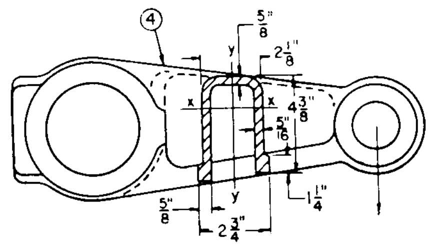
a) Oval section. A 21 ksi (145 MPa) load about the x-axis, and a 13.4 ksi (92 MPa) load about the y-axis produce outer fibre stresses of 100 ksi (690 MPa).



b) I-beam section. Application of the same loads as (a) produces outer fibre stresses of 34 ksi (234 MPa) and 87 ksi (600 MPa) respectively.



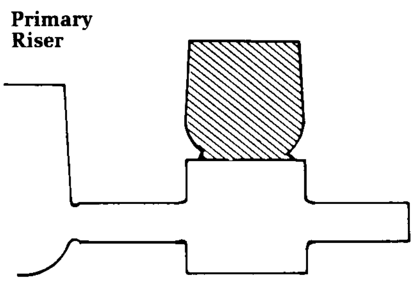
c) Cast box section. Application of the same loads as (a) produces outer fibre stresses of 37 ksi (255 MPa) and 45 ksi (310 MPa) respectively.



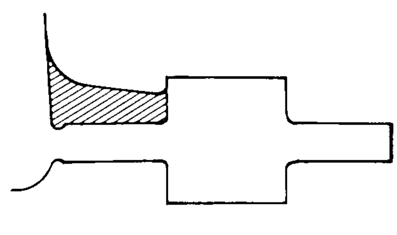
d) Cast U-section. Application of the same loads as (a) produces outer fibre stresses of 44 ksi (303 MPa) and 27 ksi (100 MPa) respectively.

Effect of design on lever performance.

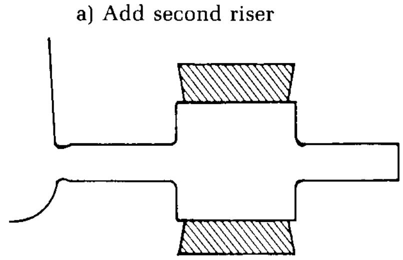
Figure 10.2



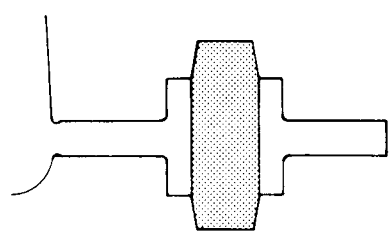
a) Add second riser



b) Add pad for feeding



c) Add chills



d) Add core to reduce mass

Methods of correcting shrinkage problems in an isolated heavy section.

bility issues related to the design of Ductile Iron castings. This Section briefly highlights some of the advantages of designing with castings and points out the additional benefits of making those castings in Ductile Iron. Detailed aspects of casting design, and further information on designing with Ductile Iron can be found in the Section references, which specialize in these subjects.

Designing with Castings

Designing with castings offers the design engineer numerous methods with which to develop a better product in shorter time at lower cost. In order to take full advantage of these opportunities, the design engineer must follow certain principles of Ductile Iron casting design. The most important of these principles are:

- use the design freedom offered by the casting process to optimize component performance, and
- design for casting soundness and freedom from defects.

Freedom of Design

The freedom of design inherent in the casting process is the ideal complement to the electronic design tools – CADCAM, solid modelling and FEA – which enable ''electronic prototyping'' to rapidly determine the optimum component shape and convert that shape into patterns for the production of castings. This process not only reduces product development time but also minimizes the need for fabricated prototypes which often ''compromise'' designs and perpetuate the compromise by becoming the production method.

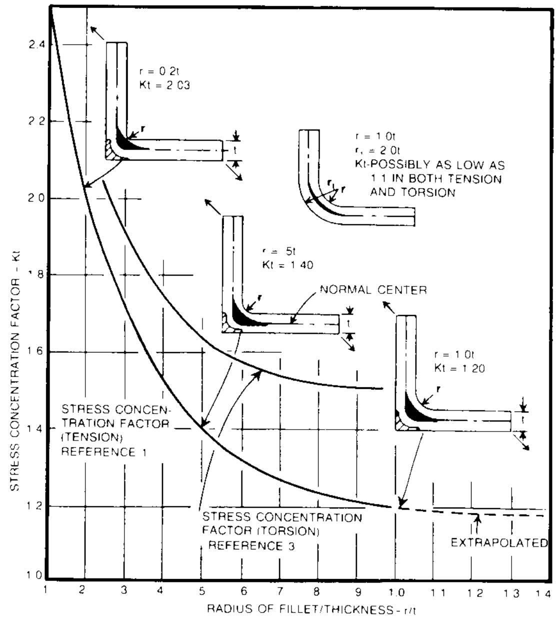
Figure 10.1 illustrates how freedom of design enables castings to provide superior component performance. In this example, the easily cast box and ''U'' sections of the lever provide lower outer fibre stresses than the oval and I-beam sections. When produced as castings this lever, and numerous similar components, have more efficient load-bearing capabilities, enabling them to be either up-rated in performance or reduced in weight without increasing tensile or fatigue design stresses.

Casting Soundness

The economical production of castings free from harmful shrinkage is a prequisite of good design. Because most cast metals shrink during solidification, prevention of shrinkage defects involves the use of directional solidification to produce feeding paths from attached feeders (risers) to every part of the solidifying castings and the avoidance of casting geometry which impairs the ability of the mold to extract heat from the soldifying casting. One of the major feeding problems is isolated sections which, due to size and geometry, soldify more slowly and cannot be fed through attached sections. ''L'', ''T'' and ''X'' junctions, with their associated right – and acute – angled surface geometries, are common hot spots in castings which should be avoided or modified to reduce both shrinkage and stress concentrations.

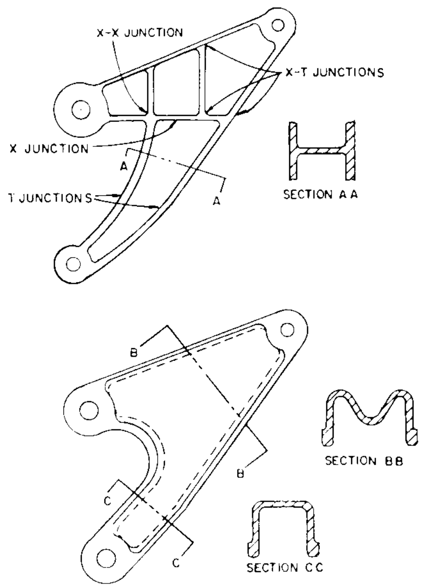
Figure 10.2 illustrates common methods for correcting shrinkage problems in isolated heavy sections. The use of risers and padding in-

Figure 10.3



Relationships between corner radii, stress concentration and castability of L-junctions. The dark areas delimiate the zone of liquid metal in the junction when freezing has just been completed in the connecting members.

Figure 10.4



Improving a bracket design by streamlining ribbed sections to eliminate T, X and X-X junctions.

crease metal consumption and casting cleaning costs while chills increase molding costs. The ideal solution is to used cored holes to induce cooling, reduce weight and eliminate machining operations. The unique solidification behaviour of Gray and Ductile Irons (see Section II) minimizes shrinkage and feeding problems, offering significant design advantages and cost savings in the production of complex castings.

The inability of mold corners, especially acute angles, to extract heat retards freezing and brings the local thermal centre near the casting surface. These problems, which may occur at any sufficiently sharp change in casting surface direction, and the reduced cooling surfaces of multi-legged junctions, require the modification of these junctions to improve casting integrity. Figure 10.3 shows how increasing L-junction radii reduces the stress concentration factor and drives the thermal center of the junction away from the casting surface. Figure 10.4 shows a component was changed from a rectilinear, junction-filled design typical of fabrications, to a more castable and efficient curvelinear design of equivalent or superior strength.

Freedom from Defects

Section XI describes the integration of design and ordering to provide superior value to the end user and profitability to both the manufacturer and foundry. One key aspect of this new concept is simultaneous design, in which component value is optimized through concurrent improvements in performance, quality, supply and manufacturability. Designing for freedom from defects is a good example of simultaneous design involving the cooperation of the designer and foundry.

Consultation

This Section is only a primer on casting design and the designer is urged to consult the references, or better still, contact a Ductile Iron foundry, the Ductile Iron Marketing Group or any of its member companies. Survival and profitability for both the users and suppliers of castings requires not only high quality castings, but increased consultations on all aspects of quality, performance and manufacturability.

REFERENCES

Designs in Ductile Iron, The Ductile Iron Group, 1467 N. Elston Ave., Suite 200, Chicago IL 60622.

Ductile Iron Castings, Produced by the British Cast Iron Research Association, Alvechurch, Birmingham B48 7QB, England, in cooperation with member companies of BRIDUC.

J. B. Caine, Design of Ferrous Castings, American Foundrymen's Society, Des Plaines, IL, 1984.

J. C. Morrison and K.J. Smith, "Cost effective substitution of steel components by SG ductile iron.", The Foundryman, March 1989, pp 121-129.

S. I. Karsay, Ductile Iron II, Quebec Iron and Titanium Corporation, 1972.

A Design Engineer's Digest of Ductile Iron, 7th Edition, 1990, QIT-Fer et Titane Inc., Montreal, Quebec, Canada.

Casting Design as Influenced by Foundry Practice, Meehanite Worldwide, Chattanooga, TN.

ASTM 65-45-12 As-Cast (1,000 to 10,000 micro strain)

Fatigue Strength Coefficient (ksi)	118.64
Fatigue Strength Exponent	-0.08939
Fatigue Ductility Coefficient (inch/inch)	0.2257
Fatigue Ductility Exponent	-0.6718

ASTM 65-45-12 Annealed (60-40-18) (1,500 to 30,000 micro strain)

Fatigue Strength Coefficient (ksi)	112.29
Fatigue Strength Exponent	-0.07052
Fatigue Ductility Coefficient (inch/inch)	0.1249
Fatigue Ductility Exponent	-0.6256

ASTM 80-55-06 As-Cast (1,380 to 30,000 micro strain)

Fatigue Strength Coefficient (ksi)	147.84
Fatigue Strength Exponent	-0.08205
Fatigue Ductility Coefficient (inch/inch)	0.2634
Fatigue Ductility Exponent	-0.6477

ASTM 80-55-06 Normalized (100-70-03) (1,650 to 30,000 micro strain)

Fatigue Strength Coefficient (ksi)	141.91
Fatigue Strength Exponent	-0.07048
Fatigue Ductility Coefficient (inch/inch)	0.1235
Fatigue Ductility Exponent	-0.5502

Table 10.2 Ductile Iron Cyclic Fatigue Properties. (Information furnished courtesy of Meritor Automotive Inc., Troy, Michigan 1997).

Courtesy of Applied Process Inc.

ADI gears with as-cast teeth.

SECTION X

SECTION XI

ORDERING CASTINGS

1. Preliminary Design
2. Supplier Selection
3. Final Design
4. Formalize Quality Management System
5. Order Castings

Table 11.1 **Stages Involved in Ordering Castings.**

1. Does the foundry have a written policy stating its quality objectives?
2. Do the foundry's quality objectives include a strong commitment to quality and the continual improvement of quality?
3. Does the foundry have an operating quality system that commits and enables all foundry employees to meet the foundry's quality objectives?
4. Can the foundry demonstrate that its processes have the capability of producing castings consistently within specification?
5. Does the foundry use quality achievement tools such as FMEA and SPC to continually improve its process capabilities?
6. Does the foundry have an internal quality audit and evaluation system to ensure that all quality procedures are being followed?
7. Does the foundry have manuals defining all standard operating practices and quality procedures?
8. Does the foundry have a policy for periodically evaluating and updating all manuals to reflect current practices?

Table 11.2 **A checklist for evaluating the commitment of potential foundry partners to quality conformance and improvement.**

ORDERING CASTINGS

The process of ordering a casting should define and support the cooperative working relationship between customer and foundry leading to the development and production of castings which provide complete satisfaction to the end user and profit to both the customer and foundry.

Introduction

To survive and prosper in the face of intense international competition, manufacturers are adopting an innovative approach to product development that affects not only their own companies but also their casting suppliers. This new approach uses the concept of multifunctional, interactive team design to improve overall product quality and performance, reduce manufacturing costs, and shorten product development time. This concept also imposes a new role on foundries who are coopted as partners into an extended, vertically integrated manufacturing system. In their new role as preferred suppliers, foundries must have the capability to not only supply quality assured products on time and at competitive cost, but also provide services that assist in the design, manufacturing and marketing of their customers' products.

The Ordering Process

In order to define and support the working partnership between customer and foundry, ordering castings has been changed from a simple commercial transaction to a multi-stage process that begins with the preliminary design of the casting and ends with qualification of the foundry for the production of commercial castings (Table 11.1).

Preliminary Design

The objective of this stage is to establish a sufficiently clear definition of the general performance requirements of the casting to permit a selection of candidate materials and production methods and to begin the definition of supplier performance standards. However, supplier selection should begin at the earliest possible point in the design process to take advantage of the expertise of the foundry partners.

Supplier Selection

Selecting the right foundry partner can be the most important part of the purchasing process. Many of the selection criteria depend on the customer's particular casting needs, but some of the most important criteria are assuming universal, and non-negotiable, status. The most important customer-specific criterion is the need for a good "fit" between the customer's requirements and the foundry's strengths. The need for "fit" is becoming more important as foundries become increasingly specialized in order to become the preferred supplier in targeted "niche markets". Categories in which fit is important are casting properties, production characteristics and foundry capability. Significant casting variables include size, complexity, dimensional accuracy, surface finish, composition and properties. Casting volume is one the more significant production variables. Critical foundry capabilities that can vary significantly according to market specialization include quality and cost control, production flexibility, expertise and customer service.

SECTION XI

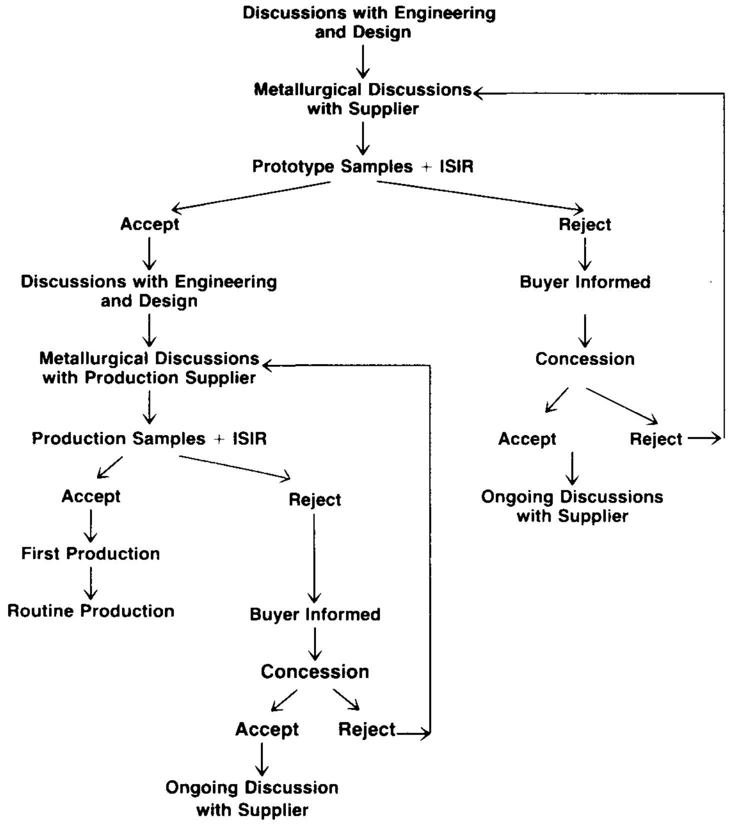


Figure 11.1 **Casting design cycle leading to production of approved castings.**

COST = PURCHASE PRICE + TOTAL MANUFACTURING COST

= PURCHASE PRICE + PRODUCTION COST + COST OF NONCONFORMANCE

= PURCHASE PRICE + PRODUCTION COST + COST OF SERVICE
+ COST OF LOST PRODUCTIVITY
+ COST OF SHIPPING REJECTS
+ COST OF PROCESS ADJUSTMENT
+ COST OF SCRAP & REWORK
+ COST OF ADMINISTRATION
+ COST OF DISTRACTION
+ COST OF REPUTATION

VALUE = QUALITY/COST

Table 11.3 **The product value equation.**

SECTION XI

Conformance to quality and delivery requirements and competitive pricing are becoming universal and necessary criteria for supplier selection. Of these, the ability to meet quality requirements, and a commitment to continuous quality improvement are the most fundamental characteristics of a preferred supplier. These characteristics can be identified and evaluated with a supplier audit which follows the checklist shown in Table 11.2. The achievement of conforming and continuously improving quality enables the foundry to meet both quality and delivery requirements, offer competitive prices and provide other quality-related benefits such as increased manufacturability and component reliability.

"Competitive price" should be a significant but subordinate criterion for supplier selection. Awarding business to the lowest bidder, or using multiple suppliers to keep casting prices low is rarely a successful strategy to reduce production costs and increase component value. When price is given undue importance in the purchasing decision, the successful bidder often sacrifices casting quality and consistency. Similarly, when the multiple supplier strategy is used, inter-supplier variations reduce casting consistency. Thus, regardless of the method used, awarding business on purchase price alone will eventually lead to reduced casting consistency and process capability, increased production and nonconformance costs and decreased component quality. Although simplistic, the product value equations in Table 11.3 serve as a warning that minimizing casting purchase price may result in increased costs, decreased quality and decreased value of the finished product. As the value added to the casting by the customer increases, casting price becomes less important and the negative consequences of low casting quality become more dominant.

Final Design

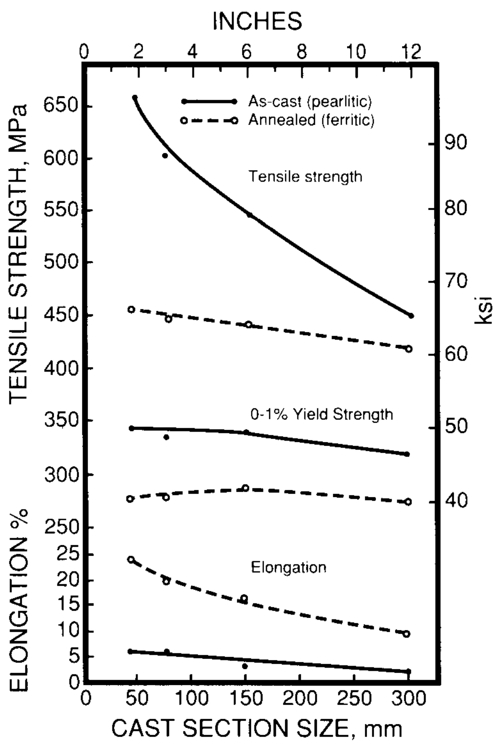
Final design is an iterative process involving close cooperation and liaison between the customer's design team and the foundry. As shown in Figure 11.1, the casting under development is cycled through successive design-feedback loops using first prototypes and then production samples until successful commercial castings are produced. After each successful design modification, operating plans are modified and appropriate conformance limits established. Although acting only as an advisor to the customer's design team, the foundry can play a critical role in optimizing casting performance and minimizing casting costs.

Final design activities should also include the cooperative efforts of both customer and foundry to reduce casting and manufacturing costs while maintaining or increasing product quality. Casting costs may be reduced by increasing overall process yield, reducing molding and coremaking costs, reducing casting cleaning costs and eliminating over-specification of the casting dimensions, composition and properties. Manufacturing cost may be reduced by increasing foundry process capabilities in dimensional and hardness control to reduce machining costs and redesigning the casting to simplify manufacturing procedures and increase productivity.

Formalizing Quality Management

This final step in the ordering process ensures that both the customer and foundry have clarified and defined all casting properties that are critical to manufacturability and product quality and have agreed upon appropriate quality assurance methodology. In this important area of specifying critical casting properties the foundry can play a very constructive role in pointing out the sensitivity of the mechanical properties to casting section size (Figure 11.2). This sensitivity to section size can be reduced significantly by employing high purity change materials, correct metal composition, special inoculation techniques, and methods to cool the section quicker.

Figure 11.2



Effect of casting section size on mechanical properties in heavy section castings.

REFERENCES

Robert C. Rodgers, "How Caterpillar Buys Castings.", Casting Design & Application, Winter 1990 pp 24-33.

J. Summerill, "Effective customer/foundry liaison is vital.", Castings to Satisfy Our Customers, a BCIRA Members' Conference, September 25-26, 1989.

E. J. Broeker, "Build a Better Supplier-Customer Relationship.", Quality Progress, September, 1989, pp 67-68.

"Deming's Point Four: A Study.", Quality Progress, December,1988, pp 31-35.

A Design Engineer's Digest of Ductile Iron, 7th Edition, QIT-Fer et Titane Inc, 1990.

S. I. Karsay, Ductile Iron II, Quebec Iron and Titanium Corporation, 1972.

The Iron Castings Handbook, Iron Castings Society, Inc., 1981.

Casting Buyer's Guide, The American Foundrymen's Society, 5th edition, 1988.

SECTION XII

SPECIFICATIONS

SECTION XII

UNS numbers and corresponding American specifications							
Standard	**Numbers/Grades**						
UNS	**F3000**	**F32800**	**F32900**	**F33100**	**F33101**	**F33800**	**F34100**
ASTM A395		60-40-18					
ASTM A536		60-40-18		65-45-12		80-55-06	
ASTM A476							80-60-03
ASTM A716			******				
AMS					5315		5316
SAE J434	DQ & T	D4018		D4512		D5506	
MIL-I-24137					(A)		
UNS	F34800	F36200	F43000	F43001	F43002	F43003	F43004
ASTM A439			D-2	D-2B	D-2C	D-3	D-3A
ASTM A536	100-70-03	120-90-02					
SAE J434	D7003						
UNS	F43005	F43006	F43007	F43010	F43020	F43021	F43030
ASTM A439	D-4	D-5	D-5B				
ASTM A571				D-2M			
AMS							5395
MIL-I-24137					(B)	(C)	

SPECIFICATIONS

Introduction

The purpose of standard specifications for Ductile Iron castings is to provide a body of information which can be used with confidence by both designer and foundry to select, define and agree upon a set of specific properties which will ensure that the castings meet the intended use of the designer. The use of standard specifications simplifies the purchase of castings from multiple suppliers because it defines a standard casting whose properties meet the designer's needs, regardless of where, or how the castings were produced.

Specifications should be chosen carefully and used sparingly to ensure that they adequately define the designer's needs without adding superfluous constraints which needlessly restrict the suppliers' options, complicate the casting process and increase the cost of the casting. It is the responsibility of both the designer and the foundry to be aware of the role and the limitations of specifications and to agree upon a specification that provides the optimum ratio of performance to cost. It is up to the designer to specify a set of properties – mechanical, physical, chemical or dimensional – which best suit the casting to its purpose.

Once the specification has been selected, the foundry must ensure that all castings delivered meet or exceed the specification. The raw materials and production methods used by the foundry to provide conforming castings are not normally restricted by the designer or the specification unless the specification includes such instructions, or the designer and foundry agree to append additional instructions to a specification. Such instructions should be used judiciously, because they almost invariably increase the casting cost and restrict the number of foundries which can provide competitive bids.

North America

The ASTM has five standards covering Ductile Iron castings. ASTM A 536 is the most frequently used, covering the general engineering grades of Ductile Iron. The other standards cover austenitic and special Ductile Iron applications. The ASTM has issued in 1990 a new specification defining the properties of Austempered Ductile Iron. The SAE standard J434 is commonly used for specifying automotive Ductile Iron castings. In an attempt to create a single, comprehensive system for designating metals and alloys the ASTM and SAE have jointly developed the Unified Numbering System (UNS). While not itself a specification, the UNS designation is gaining some degree of acceptance in North America as a useful means of simplifying and correlating the various existing specifications. The UNS designations for Ductile Irons, cross-referenced to the corresponding ASTM, AMS, SAE and MIL specifications, are shown on the opposite page.

Other Standards

This section also summarizes the national standards for Ductile Iron for the other major industrialized countries and the international ISO standard. This standard, and its replacement, the EuroNorm standard EN will become increasingly important with the growth of the European Community. There are many additional standards for Ductile Iron, some national, and others valid only within a specific technical or commercial organization. While each specification may have its own distinguishing characteristics, there are also many similarities between specifications. Before using any specification, the designer should obtain a complete copy of the current issue from the specifying body to familiarize himself with both the properties specified and the conditions under which they are to be measured.

Standard specifications for Ductile Iron are normally based on mechanical properties, except for those defining austenitic Ductile Iron, which are based on composition. Mechanical property values are given in the units normal to the particular specifying body. Conversions for SI, metric non-SI, and non-metric units are given at the end of this section to assist in comparing specifications.

Beyond Specifications

Standards and specifications ensure uniformity and assist both the designer and the foundry in defining the most important properties of the castings. However, most of the specifications identify either minimum properties, or ranges of properties, inferring that all castings whose properties either exceed the minimum or lie anywhere within the range, are equally acceptable. This inference is incorrect, and high quality castings, whose properties either consistently exceed requirements, or fall well within specified ranges, offer the designer a competitive edge. Through commitments to SPC and continual quality improvement, many foundries have developed the capability to produce castings whose higher quality can be demonstrated statistically. Designers should take advantage of these capabilities to obtain assured quality which is superior to that required by specifications.

SECTION XII

REFERENCES

Annual Book of ASTM Standards, Volume 01.02, Ferrous Castings, 1997.

I. C. H. Hughes, "Ductile Iron," *Metals Handbook,* American Society for Metals, Vol. 15, 9th edition, 1988.

American Society of Automotive Engineers Inc., Warrendale, PA, 1989.

ASTM A 395 — FERRITIC DUCTILE IRON PRESSURE-RETAINING CASTINGS FOR USE AT ELEVATED TEMPERATURES

This standard specifies chemical, physical, and hardness requirements.

Chemical Requirements

The castings shall conform to the following requirements for chemical composition (Note 3):

Total carbon, min, %	3.00
Silicon, max, %	2.50
Phosphorus, max, %	0.08

Physical Requirements

Tensile Properties – The Ductile Iron as represented by the test specimens shall conform to the following requirements for tensile properties:

Tensile strength, min, psi (MPa)	60 000 (414)
Yield strength, min, psi (MPa)	40 000 (276)
Elongation in 2 in. or 50 mm min.	18%

Hardness: – The hardness of the heat-treated Ductile Iron as represented by the test specimens and castings shall be within the following limits:

HB, 3000-kgf load	143 to 187

ASTM A 439 — AUSTENITIC DUCTILE IRON CASTINGS

Chemical Requirements

Element	D-2[A]	D-2B	D-2C	D-3[A]	D-3A	D-4	D-5	D-5B	D-5S
	Composition, %								
Total carbon, max	3.00	3.00	2.90	2.60	2.60	2.60	2.40	2.40	2.30
Silicon	1.50-3.00	1.50-3.00	1.00-3.00	1.00-2.80	1.00-2.80	5.00-6.00	1.00-2.80	1.00-2.80	4.90-5.50
Manganese	0.70-1.25	0.70-1.25	1.80-2.40	1.00 max[B]	1.00 max[B]	1.00 max[B]	1.00 max[B]	1.00 max[B]	1.00 max
Phosphorus, max	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Nickel	18.00-22.00	18.00-22.00	21.00-24.00	28.00-32.00	28.00-32.00	28.00-32.00	34.00-36.00	34.00-36.00	34.00-37.00
Chromium	1.75-2.75	2.75-4.00	0.50 max[B]	2.50-3.50	1.00-1.50	4.50-5.50	0.10 max	2.00-3.00	1.75-2.25

[A] Additions of 0.7 to 1.0% of molybdenum will increase the mechanical properties above 800°F (425°C).
[B] Not intentionally added.

Mechanical Requirements

Element	D-2	D-2B	D-2C	D-3	D-3A	D-4	D-5	D-5B	D-5S
	Properties								
Tensile strength, min, ksi (MPa)	58 (400)	58 (400)	58 (400)	55 (379)	55 (379)	60 (414)	55 (379)	55 (379)	65 (449)
Yield strength (0.2 percent offset), min, ksi (MPa)	30 (207)	30 (207)	28 (193)	30 (207)	30 (207)	–	30 (207)	30 (207)	30 (207)
Elongation 2 in. or 50 mm, min, %	8.0	7.0	20.0	6.0	10.0	–	20.0	6.0	10
Brinell hardness (300 kg)	139-202	148-211	121-171	139-202	131-193	202-273	131-185	139-193	131-193

SECTION XII

ASTM A 476 DUCTILE IRON CASTINGS FOR PAPER MILL DRYER ROLLS

Chemical Requirements

The castings shall conform to the following chemical requirements:

Total carbon, min, %	3.0
Silicon, max, %	3.0
Phosphorus, max, %	0.08
Sulfur, max, %	0.05

The castings shall have a carbon equivalent of 3.8 to 4.5 inclusive.

Tensile Requirements

Test Coupon Section Thickness	1 in.	3 in.
Tensile strength, min, ksi	80	80
Yield strength, min, ksi	60	60
Elongation in 2 in., min, %	3.0	1.0

ASTM A 536 DUCTILE IRON CASTINGS

Tensile Requirements

	Grade 60/40/18	Grade 65/45/12	Grade 80/55/06	Grade 100/70/03	Grade 120/90/02
Tensile strength, min, psi	60 000	65 000	80 000	100 000	120 000
Tensile strength, min, MPa	414	448	552	689	827
Yield strength, min, psi	40 000	45 000	55 000	70 000	90 000
Yield strength, min, MPa	276	310	379	483	621
Elongation in 2 in. or 50 mm, min, %	18	12	6.0	3.0	2.0

Tensile Requirements for Special Applications

	Grade 60/42/10	Grade 70/50/05	Grade 80/60/03
Tensile strength, min, psi	60 000	70 000	80 000
Tensile strength, min, MPa	415	485	555
Yield strength, min, psi	42 000	50 000	60 000
Yield strength, min, MPa	290	345	415
Elongation in 2 in. or 50 mm, min, %	10	5	3

ASTM A 571 AUSTENITIC DUCTILE IRON CASTINGS FOR PRESSURE-CONTAINING PARTS SUITABLE FOR LOW-TEMPERATURE SERVICE

This standard specifies that all castings shall be heat treated by annealing between 1600 and 1800°F for 1 hour per inch of casting section and furnace cooling.

Chemical Requirements

Element	Composition, %
Total carbon	2.2-2.7[A]
Silicon	1.5-2.50
Manganese	3.75-4.5
Nickel	21.0-24.0
Chromium	0.20 max
Phosphorus	0.08 max

[A] For castings with sections under 1/4 in., it may be desirable to adjust the carbon upwards to a maximum of 2.90%.

Mechanical Property Requirements[A]

	Class 1	Class 2
Tensile Strength, min, ksi	65	60
Yield Strength 0.2% (offset), min, ksi	30	25
Elongation, min, %	30	25
Brinell Hardness, 3000 kg	121-171	111-171
Charpy V-notch, ft-lbf		
min, average 3 tests	15	20
min, individual test	12	15

[A] Heat-treated condition

ASTM A 897 A 897 M AUSTEMPERED DUCTILE IRON

Grade	Min. Tensile Str.		Min. Yield Str.		Elongation	Impact Energy*		Hardness
	MPa	Ksi	MPa	Ksi	Percent	Joules	Ft-lb	BHN**
125/80/10		125		80	10		75	269-321
850/550/10	850		550		10	100		269-321
150/100/7		150		100	7		60	302-363
1050/700/7	1050		700		7	80		302-363
175/125/4		175		125	4		45	341-444
1200/850/4	1200		850		4	60		341-444
200/155/1		200		155	1		25	388-477
1400/1100/1	1400		1100		1	35		388-477
230/185/–		230		185	***		***	444-555
1600/1300/–	1600		1300		***	***		444-555

* Values obtained using unnotched Charpy bars tested at 72 deg. F (20 deg. C). The values in the table are the average of the three highest of four tested samples.
** Hardness is not a mandatory specification and is shown for information only.
*** Elongation and impact specifications are not required.

Complete specifications may be obtained from:
American Society for Testing Materials, 100 Barr Harbor Drive, West Conshocken, PA 19428.
Society of Automotive Engineers Inc., 485 Lexington Ave., New York NY 10017.
American Society of Mechanical Engineers, 345 East 47th Street, New York NY 10017.

NOTE: SAE specification for Ductile Iron casting and austempered Ductile Iron casting are currently been revised so they were not available as of the time of this printing.

SAE J434C AUTOMOTIVE DUCTILE IRON CASTINGS

Grade	Tensile strength, R_{m1} min.				Proof stress, $R_{po.2}$ min.				Elongation A, min.	Hardness	Structure
	N/mm²	kgf/mm²	tonf/in²	lbf/in²	N/mm²	kgf/mm²	tonf/in²	lbf/in²	%	HB	
D4018	414	42.2	26.8	60 000	276	28.1	17.9	40 000	18	170 max.	Ferrite
D4512	448	45.7	29.0	65 000	310	31.6	20.1	45 000	12	156-217	Ferrite & pearlite
D5506	552	56.2	35.7	80 000	379	38.7	24.6	55 000	6	187-255	Ferrite & pearlite
D7003	689	70.3	44.6	100 000	483	49.2	31.3	70 000	3	241-302	Pearlite
DQ&T**	-	-	-	-	-	-	-	-	-	-	Martensite

*These irons are primarily specified on hardness and structure. The mechanical properties are given for information only.
**Quenched and tempered grade; hardness to be agreed between supplier and purchaser.

JAPAN JIS G 5503-1995 AUSTEMPERED SPHEROIDAL GRAPHITE IRON CASTINGS

Mechanical properties of separately cast test sample

Symbol of grade	Tensile strength N/mm²	Yield strength N/mm²	Elongation %	Hardness HB
FCAD 900-4	900 min.	600 min.	4 min.	-
FCAD 900-8	900 min.	600 min.	8 min.	-
FCAD 1000-5	1000 min.	700 min.	5 min.	-
FCAD 1200-2	1200 min.	900 min.	2 min.	341 min.
FCAD 1400-1	1400 min.	1100 min.	1 min.	401 min.

JAPAN
JIS G 5502-1995

SPHEROIDAL GRAPHITE IRON CASTINGS

Mechanical properties of separately cast test sample

Symbol of grade	Tensile strength N/mm²	Yield strength N/mm²	Elongation %	Charpy absorption energy			(Informative reference)	
				Test Temperature °C	Mean value of 3 pieces J	Individual value J	Hardness HB	Matrix structure
FCD 350-22	350 min.	220 min.	22 min.	23 ± 5	17 min.	14 min.	150 max.	Ferrite
FCD 350-22L				-40 ± 2	12 min.	9 min.		
FCD 400-18	400 min.	250 min.	18 min.	23 ± 5	14 min.	11 min.	130 to 180	
FCD 400-18L				-20 ± 2	12 min.	9 min.		
FCD 400-15			15 min.	–	–	–		
FCD 450-10	450 min.	280 min.	10 min.				140 to 210	
FCD 500-7	500 min.	320 min.	7 min.				150 to 230	Ferrite + pearlite
FCD 600-3	600 min.	370 min.	3 min.				170 to 270	Pearlite + ferrite
FCD 700-2	700 min.	420 min.	2 min.				180 to 300	Pearlite
FCD 800-2	800 min.	480 min.					200 to 330	Pearlite or tempered structure

Mechanical properties of cast-on test sample

Symbol of grade	Chief thickness of iron casting mm	Tensile strength N/mm²	Yield strength N/mm²	Elongation %	Charpy absorption energy			(Informative reference)	
					Test Temperature °C	Mean value of 3 pieces J	Individual value J	Hardness HB	Matrix structure
FCD 400-18A	Over 30, up to and incl. 60	390 min.	250 min.	15 min.	23 ± 5	14 min.	11 min.	120 to 180	Ferrite
	Over 60, up to and incl. 200	370 min.	240 min.	12 min.		12 min.	9 min.		
FCD 400-18AL	Over 30, up to and incl. 60	390 min.	250 min.	15 min.	-20 ± 2				
	Over 60, up to and incl. 200	370 min.	240 min.	12 min.		10 min.	7 min.		
FCD 400-15A	Over 30, up to and incl. 60	390 min.	250 min.	15 min.	–	–	–		
	Over 60, up to and incl. 200	370 min.	240 min.	12 min.					
FCD 500-7A	Over 30, up to and incl. 60	450 min.	300 min.	7 min.				130 to 230	Ferrite + pearlite
	Over 60, up to and incl. 200	420 min.	290 min.	5 min.					
FCD 600-3A	Over 30, up to and incl. 60	600 min.	360 min.	2 min.				160 to 270	Pearlite + ferrite
	Over 60, up to and incl. 200	550 min.	340 min.	1 min.					

EUROPEAN STANDARD EN 1563:1997 — SPHEROIDAL GRAPHITE CAST IRONS

Mechanical properties measured on test pieces machined from separately cast samples

Material designation		**Tensile strength** R_m N/mm²	**0.2% proof stress** $R_{p0.2}$ N/mm²	**Elongation** A %
Symbol	**Number**	**min.**	**min.**	**min.**
EN-GJS-350-22-LT[1)]	EN-JS1015	350	220	22
EN-GJS-350-22-LT[2)]	EN-JS1014	350	220	22
EN-GJS-350-22-LT	EN-JS1010	350	220	22
EN-GJS-400-18-LT[1)]	EN-JS1025	400	240	18
EN-GJS-400-18-LT[2)]	EN-JS1024	400	250	18
EN-GJS-400-18-LT	EN-JS1020	400	250	18
EN-GJS-450-15	EN-JS1030	400	250	15
EN-GJS-450-10	EN-JS1040	450	310	10
EN-GJS-500-7	EN-JS1050	500	320	7
EN-GJS-600-3	EN-JS1060	600	370	3
EN-GJS-700-2	EN-JS1070	700	420	2
EN-GJS-800-2	EN-JS1080	800	480	2
EN-GJS-900-2	EN-JS1090	900	600	2

1) LT for low temperature.
2) RT for room temperature.

NOTE 1. The values for these materials apply to castings cast in sand moulds of comparable thermal diffusivity. Subject to amendments to be agreed upon in the order, they can apply to castings obtained by alternative methods.

NOTE 2. Whatever the method used for obtaining the castings, the grades are based on the mechanical properties measured on test pieces taken from samples separately cast in a sand mould or a mould of comparable thermal diffusivity.

NOTE 3. 1 N/mm² is equivalent to 1 MPa.

NOTE 4. The material designation is in accordance with EN 1560.

Minimum impact resistance values measured on V-notched test pieces machined from separately cast samples

Material designation		**Minimum impact resistance values (in J)**					
		At room temperature (23 ± 5) °C		**At (-20 ± 2) °C**		**At (-40 ± 2) °C**	
Symbol	**Number**	**Mean value from 3 tests**	**Individual value**	**Mean value from 3 tests**	**Individual value**	**Mean value from 3 tests**	**Individual value**
EN-GJS-350-22-LT[1)]	EN-JS1015	–	–	–	–	12	9
EN-GJS-350-22-RT[2)]	EN-JS1014	17	14	–	–	–	–
EN-GJS-400-18-LT[1)]	EN-JS1025	–	–	12	9	–	–
EN-GJS-400-18-LT[2)]	EN-JS1024	14	11	–	–	–	–

1) LT for low temperature.
2) RT for room temperature.

NOTE 1. The values for these materials apply to castings cast in sand moulds of comparable thermal diffusivity. Subject to amendments to be agreed upon in the order, they can apply to castings obtained by alternative methods.

NOTE 2. Whatever the method used for obtaining the castings, the grades are based on the mechanical properties measured on test pieces taken from samples separately cast in a sand mould or a mould of comparable thermal diffusivity.

NOTE 3. The material designation is in accordance with EN 1560.

Mechanical properties measured on test pieces machined from separately cast samples

Material designation: Symbol	Material designation: Number	Relevant wall thickness t mm	Tensile strength R_m N/mm² min.	0.2% proof stress $R_{p0.2}$ N/mm² min.	Elongation A % min.
EN-GJS-350-22U-LT[1)]	EN-JS1019	$t \leq 30$	350	220	22
		$30 < t \leq 60$	330	210	18
		$60 < t \leq 200$	320	200	15
EN-GJS-350-22U-RT[2)]	EN-JS1029	$t \leq 30$	350	220	22
		$30 < t \leq 60$	330	220	18
		$60 < t \leq 200$	320	210	15
EN-GJS-350-22U	EN-JS1032	$t \leq 30$	350	220	22
		$30 < t \leq 60$	330	220	18
		$60 < t \leq 200$	320	210	15
EN-GJS-400-18U-LT[1)]	EN-JS1049	$t \leq 30$	400	240	18
		$30 < t \leq 60$	390	230	15
		$60 < t \leq 200$	370	220	12
EN-GJS-400-18U-RT[2)]	EN-JS1059	$t \leq 30$	400	250	18
		$30 < t \leq 60$	390	250	15
		$60 < t \leq 200$	370	240	12
EN-GJS-400-18U	EN-JS1062	$t \leq 30$	400	250	18
		$30 < t \leq 60$	390	250	15
		$60 < t \leq 200$	370	240	12
EN-GJS-400-15U	EN-JS1072	$t \leq 30$	400	250	15
		$30 < t \leq 60$	390	250	14
		$60 < t \leq 200$	370	240	11
EN-GJS-450-10U	EN-JS1132	$t \leq 30$	450	310	10
		$30 < t \leq 60$ $60 < t \leq 200$	To be agreed between the manufacturer and the purchaser.		
EN-GJS-500-7U	EN-JS1082	$t \leq 30$	500	320	7
		$30 < t \leq 60$	450	300	7
		$60 < t \leq 200$	420	290	5
EN-GJS-600-3U	EN-JS1092	$t \leq 30$	600	370	3
		$30 < t \leq 60$	600	360	2
		$60 < t \leq 200$	550	340	1
EN-GJS-700-2U	EN-JS1102	$t \leq 30$	700	420	2
		$30 < t \leq 60$	700	400	2
		$60 < t \leq 200$	660	380	1
EN-GJS-800-2U	EN-JS1112	$t \leq 30$	800	480	2
		$30 < t \leq 60$ $60 < t \leq 200$	To be agreed between the manufacturer and the purchaser.		
EN-GJS-900-2U	EN-JS1122	$t \leq 30$	900	600	2
		$30 < t \leq 60$ $60 < t \leq 200$	To be agreed between the manufacturer and the purchaser.		

1) LT for low temperature.
2) RT for room temperature.

NOTE 1. The properties of a cast-on test piece cannot reflect exactly the properties of the casting itself, but can be a better approximation than those obtained on a separately cast sample. Further values are given in annex D for guidance.

NOTE 2. 1 N/mm² is equivalent to 1 MPa.

NOTE 3. The material designation is in accordance with EN 1560.

Material designation		Brinell hardness range HB	Other properties (for information only)	
			R_m	$R_{p0.2}$
Symbol	Number		N/mm²	N/mm²
EN-GJS-HB130	EN-JS2010	Less than 160	350	220
EN-GJS-HB150	EN-JS2020	130 to 175	400	250
EN-GJS-HB155	EN-JS2030	135 to 180	400	250
EN-GJS-HB185	EN-JS2040	160 to 210	450	310
EN-GJS-HB200	EN-JS2050	170 to 230	500	320
EN-GJS-HB230	EN-JS2060	190 to 270	600	370
EN-GJS-HB265	EN-JS2070	225 to 305	700	420
EN-GJS-HB300[1]	EN-JS2080[1]	245 to 335	800	480
EN-GJS-HB330[1]	EN-JS2090[1]	270 to 360	900	600

[1] EN-GJS-HB300 (EN-JS2080) and EN-GJS-HB330 (EN-JS2090) are not recommended for thick section castings.

NOTE 1. 1 N/mm² is equivalent to 1 MPa.

Minimum impact resistance values measured on V-notched test pieces machined from cast-on samples

Material designation		Relevant wall thickness t	Minimum impact resistance values (in J)					
			At room temperature (23 ± 5) °C		At (-20 ± 2) °C		At (-40 ± 2) °C	
			Mean value from 3 tests	Individual value	Mean value from 3 tests	Individual value	Mean value from 3 tests	Individual value
Symbol	Number	mm						
EN-GJS-350-22U-LT[1]	EN-JS1019	$t \leq 60$ $60 < t \leq 200$	–	–	–	–	12 10	9 7
EN-GJS-350-22U-RT[2]	EN-JS1029	$t \leq 60$ $60 < t \leq 200$	17 15	14 12	–	–	–	–
EN-GJS-400-18U-LT[1]	EN-JS1049	$30 < t \leq 60$ $60 < t \leq 200$	–	–	12 10	9 7	–	–
EN-GJS-400-18U-RT[2]	EN-JS1059	$30 < t \leq 60$ $60 < t \leq 200$	14 12	11 9	–	–	–	–

[1] LT for low temperature.
[2] RT for room temperature.

NOTE 1. The values for the materials normally apply to castings with thicknesses between 30 mm and 200 mm and with a mass greater than 2 000 kg or when the relevant wall thickness may vary between 30 mm and 200 mm.

NOTE 2. The properties of a cast-on test piece cannot reflect exactly the properties of the casting itself, but can be a better approximation than those obtained on a separately cast sample. Further values are given in annex D for guidance.

NOTE 3. 1 N/mm² is equivalent to 1 MPa.

NOTE 4. The material designation is in accordance with EN 1560.

EUROPEAN STANDARD EN 1564:1997 — AUSTEMPERED DUCTILE CAST IRONS

Mechanical properties measured on test pieces machined from separately cast samples

Material designation		Tensile strength R_m N/mm²	0.2% proof stress $R_{p0.2}$ N/mm²	Elongation A %
Symbol	**Number**	**min.**	**min.**	**min.**
EN-GJS-800-8	EN-JS1100	800	500	8
EN-GJS-1000-5	EN-JS1110	1000	700	5
EN-GJS-1200-2	EN-JS1120	1200	850	2
EN-GJS-1400-1	EN-JS1130	1400	1100	1

NOTE 1. The values for these materials apply to castings cast in sand moulds of comparable thermal diffusivity. Subject to amendments to be agreed upon in the order, they can apply to castings obtained by alternative methods.

NOTE 2. Whatever the method used for obtaining the castings, the grades are based on the mechanical properties measured on test pieces taken from samples separately cast in a sand mould or a mould of comparable thermal diffusivity.

NOTE 3. 1 N/mm² is equivalent to 1 MPa.

NOTE 4. The material designation is in accordance with EN 1560.

Hardness range

Material designation		Brinell hardness range
Symbol	**Number**	**HB**
EN-GJS-800-8	EN-JS1100	260 to 320
EN-GJS-1000-5	EN-JS1110	300 to 360
EN-GJS-1200-2	EN-JS1120	340 to 440
EN-GJS-1400-1	EN-JS1130	380 to 480

NOTE The material designation is in accordance with EN 1560.

SOUTH AFRICA SABS 936/937 — SPHEROIDAL GRAPHITE IRON CASTINGS

	Tensile strength R_m min.			Proof stress $R_{p0.2}$ min.			Elongation A min.	Hardness	
Grade	**N/mm²**	**kgf/m²**	**ton/in²**	**N/mm²**	**kgf/m²**	**ton/in²**	**%**	**HB**	**§ Structure**
SG 38	375	38.0	24.2	245	25.0	16.0	17	≤ 180	Ferrite
SG 42	410	42.0	2.5	275	28.1	17.7	12	≤ 200	Ferrite
SG 50	490	50.0	31.7	345	35.2	22.3	7	§ 170 - 240	Ferrite & pearlite
SG 60	590	60.0	38.1	390	39.8	25.2	4	§ 210 - 250	Pearlite
SG 70	685	70.0	44.4	440	44.9	28.5	3	§ 230 - 300	Pearlite
SG 80	785	80.0	50.8	490	50.0	31.7	2	§ 260 - 330	Pearlite or temper structure

§ For information only.

SOUTH AFRICA AUSTEMPERED DUCTILE IRON CASTINGS
SABS 1656:1995

Grade	Minimum tensile strength R_m MPa	Minimum proof stress $R_{p0.2}$ MPa	Minimum elongation %	Impact strength (energy loss) J	Hardness[1)]
ADI 850	850	550	10	100	269 - 321
ADI 1050	1050	700	7	80	302 - 363
ADI 1200	1200	850	4	60	341 - 444
ADI 1400	1400	1100	1	35	388 - 477
ADI 1600	1600	1300	–	–	444 - 555

[1)] For information only.

SOUTH AFRICA AUSTENITIC SPHEROIDAL GRAPHITE IRON CASTINGS

	Tensile strength R_m min.			Proof stress $R_{p0.2}$ min.			Elongation A min.	Hardness max.
Grade	N/mm²	kgf/m²	ton/in²	N/mm²	kgf/m²	ton/in²	%	HB
ASG-2A	375	38.0	24.2	205	21.0	13.3	8	200
ASG-2B	375	38.0	24.2	205	21.0	13.3	6	255
ASG-3A	375	38.0	24.2	195	20.0	12.5	20	170
ASG-4A	375	38.0	24.2	205	21.0	13.3	10	230
ASG-5A	375	38.0	24.2	205	21.0	13.3	7	200
ASG-6A	410	42.0	26.5	205	21.0	13.3	25	170

PHYSICAL PROPERTIES OF SOME ELEMENTS

Element	Symbol	Atomic Weight	Melting Point °F	Melting Point °C	Boiling Point °F	Density grs/cc
Aluminium	Al	26.97	1220	660	3272	2.70
Antimony	Sb	121.76	1167	630	2516	6.62
Barium	Ba	137.36	1562	850	2084	3.50
Beryllium	Be	9.02	2462	1350	2732	1.82
Bismuth	Bi	209.00	520	271	2642	9.80
Boron	B	10.82	4172	2282	4622	2.30
Cadmium	Cd	112.41	610	321	1408	8.65
Calcium	Ca	40.08	1564	851	2522	1.55
Carbon	C	12.00	–	–	6512	2.22
Cerium	Ce	140.13	1427	640	2552	6.79
Chromium	Cr	52.01	3326	1812	3992	7.14
Cobalt	Co	58.94	2696	1480	5252	8.90
Columbium	Nb	92.91	3542	1932	5972	8.57
Copper	Cu	63.57	1982	1082	4259	8.94
Gold	Au	197.20	1945	1062	4712	19.30
Iron	Fe	55.84	2795	1535	5430	7.87
Lead	Pb	207.22	621	327	2948	11.35
Lithium	Li	6.94	367	186	2437	0.53
Magnesium	Mg	24.32	1204	652	2007	1.74
Manganese	Mn	54.94	2273	1245	3452	7.20
Mercury	Hg	200.61	-38	–	676	13.55
Molybdenum	Mo	96.00	4748	2602	6692	10.20
Nickel	Ni	58.69	2645	1452	5252	8.85
Palladium	Pd	106.70	2831	1555	3992	12.00
Phosphorus	P	31.02	111	42	536	1.82
Platinum	Pt	195.23	3224	1755	7772	21.45
Potassium	K	39.09	144	62	1400	0.86
Rhodium	Rh	102.91	3551	1882	4532	12.50
Selenium	Se	78.96	428	220	1270	4.81
Silicon	Si	28.06	2588	1420	4712	2.40
Silver	Ag	107.88	1761	961	3542	10.50
Sodium	Na	22.99	207	97	1616	0.97
Strontium	Sr	87.63	1472	800	2102	2.60
Sulfur	S	32.06	235	112	832	2.07
Tantalum	Ta	180.88	5162	2832	7412	16.60
Tellurium	Te	127.61	846	451	2534	6.24
Thallium	Ti	204.39	578	302	3002	11.85
Thorium	Th	232.12	3353	1827	5432	11.50
Tin	Sn	118.70	450	232	4100	7.30
Titanium	Ti	47.90	3272	1782	5432	4.50
Tungsten	W	184.00	6098	3334	10526	19.30
Uranium	U	238.14	3074	1672	6332	18.70
Vanadium	V	50.95	3110	1692	5432	5.68
Zinc	Zn	65.38	787	419	1661	7.14
Zirconium	Zr	91.22	3092	1682	5252	6.40

CONVERSIONS: English, SI units, and non-SI metric units

1 lbf/in^2	=	1 psi
1 ksi	=	1000 psi
	=	6.895 N/m^2
	=	6.895 MPa
	=	0.7031 kgf/mm^2
	=	0.4464 $tonf/in^2$
1 N/mm^2	=	1 MN/m^2
	=	1 MPa
	=	0.06475 $tonf/in^2$
	=	145.04 lbf/in^2
	=	0.10197 kgf/mm^2
1 kgf/mm^2	=	9.8067 N/mm^2
	=	0.63497 $tonf/in^2$
	=	1422.4 lbf/in^2
1 $tonf/in^2$	=	15.444 N/mm^2
	=	1.5749 kgf/mm^2
	=	2240 lbf/in^2
1 ft-lbf	=	1.3558 J
	=	0.1369 kgf-m
1 J	=	0.73757 ft-lbf
	=	0.10197 kgf-m
1kgf-m	=	9.8067 J
	=	7.3068 ft lbf

	Units English	Multiplication Factor	SI Units
Area	in^2	6.45	cm^2
Area	ft^2	.093	m^2
Length	in	2.54	cm
Length	ft	.305	m
Mass	lb	.454	kg
Temp	(°F - 32)	.556	°C

SECTION XII

Back to Table of Contents

SECTION XIII

INDEX

INDEX

SECTION XIII

D

E

F

SECTION XIII

Back to Table of Contents