"HOT TOPICS"

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A Statistical Capability Approach to Reviewing Customer Casting Specifications

By Shawn Rediske

The Problem

Customers specify casting requirements that are contradictory or unnecessary, causing foundries to incur unnecessary scrap or operating costs. Customers often write numerous – and sometimes unnecessary – requirements into their part or casting specifications. Sometimes these requirements are truly reflections of what the part needs to be able to meet design intent and to function properly. Sometimes, requirements are added as lessons learned from historical issues at castings suppliers. Sometimes, requirements are added for reasons that are…lost to history…and no one at the customer is able to provide an adequate explanation for the rationale behind the requirements.

Furthermore, customers often require foundries to show statistical capability of meeting their requirements. The drive for statistical capability is not the problem – process control that allows statistical capability will allow reduced operational costs for any foundry that can achieve them. The issue is when customers require contradictory specifications (for example, a hardness range that does not line up with mechanical properties), showing statistical capability for all requirements can become extremely difficult.

Interestingly, foundries that understand statistical capability analysis can use this understanding to prove to customers, based on historical performance, that contradictory requirements are, indeed, contradictory. These foundries can go further and propose alternative limits, "capability limits," that are reasonable, given the foundries capabilities and history.

The Goal

The goal of this discussion is to define an approach that will effectively

1. Communicate to customers which requirements are contradictory or unnecessary and why
2. Determine what limits are reasonable, given a foundry's historical performance
3. Support 1. and 2. with statistical capability analysis of historical performance

Parameters, Assertions, and Assumptions

The requirements of interest include:

1 Mechanical Properties (UTS, YS, %E)
2 Hardness
3 Impact properties (Charpy)
4 Ferrite/Pearlite Ratio
5 Nodularity (Nodularity %, Size, Count)
6 Carbides/chill (Depth, %)
7 Chemistry (C, Si, Mg, Cu, Mn, CE, AF, etc.)
8 PV Testing
9 Heat Treatment

Basically, this article outlines an approach that a major automotive foundry has used to discuss casting specifications with its customers. For this approach, the following assumptions regarding the people involved have been made:

1 The people who design castings (design engineers) understand what minimum mechanical properties their parts need.
2 The people who run machining lines (machining manufacturing/process engineers) understand their machining processes (tolerances, tool life, etc.).
3 Design engineers and machining manufacturing/process engineers are reasonable people who are trying to

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2 The people who run machining lines (machining manufacturing/process engineers) understand their machining processes (tolerances, tool life, etc.).
3 Design engineers and machining manufacturing/process engineers are reasonable people who are trying to design parts the best way that they know how, but do not understand metallurgy;

therefore, they develop specifications that they think will protect their parts, but often overspecify, creating requirements that add no value to their parts but drive cost into the foundry.

4 Foundries are casting experts; design engineers and machine shops are not. It is incumbent on the foundry to educate their customers on foundry requirements and limitations, for the benefit of the customer and the foundry.

5 The jobs that we are talking about are for the automotive OEMs. They follow AIAG. Therefore, statistical capability is the norm and the goal – it's not enough for the foundry to be able to say that they won't ship castings that fall outside of specification; it's necessary for the foundry to prove to the customer that they won't make castings that fall outside of specification.

While these assumptions may not be true in all situations – and knowingly and willfully ignore the politics that are unavoidable between the foundry and its customer – they have been adopted to maintain a coaching point of view and to avoid a more adversarial point of view.

Mechanical properties

When reviewing a customer's spec, start with the mechanical properties requirements. Foundries should consider the mechanical properties requirements as the most direct reflection of the designer's intent. Therefore, following AIAG, the foundry's burden is to prove statistical capability to the mechanical property requirements. If this can be done, the foundry can make a compelling argument that its castings will meet the design intent. The foundry can then move from this position of confidence to request changes to other, less function-critical requirements (for example, microstructural or chemical requirements).

Tensile Bars: Keel blocks vs. Casting Sections – To verify a foundry's performance on mechanical properties, tensile bars, either sectioned from the casting or taken from keel/Y blocks, are tested. Customers sometimes include notations in their specifications, requiring one type of tensile bar or the other. Both types of tensile bars have their benefits and drawbacks, and the foundry should be aware of these to make an informed choice. (Some of the key points are outlined here; for more detailed discussion, refer to Hot Topic Issue #8, 2005 on www.ductile.org.)

	Benefits	Drawbacks/Considerations
Keel/Y Blocks	•1 No need to cut and scrap a casting •2 Lower propensity for shrink (large riser, directly over test bar)	•1 Requires correlation to actual casting properties and casting process (section thickness, sand-to-metal ratio, cooling time, inoculation)
Casting Section	•2 Provides direct measure of actual casting properties	•3 Requires cutting and scrapping of a casting •4 Substandard bars (with very small tensile bar gauge diameter) are extra sensitive to casting flaws and machined test bar surface finish •5 Casting flaws in tensile bar location (inclusions, porosity) can reduce measured mechanical properties •6 SAE, EN, JIS minimum requirements are reduced with larger section sizes

Casting Section Tensile Bar Locations – When the customer requires that tensile bars be sectioned from the casting, the foundry should agree with the customer on the tensile bar location. Locations should be assessed for shrink tendency, test bar size, solidification rate, and cooling rate; if the location is a concern for any of these issues, the foundry should address that concern with the customer as early in the APQP process as possible and, if possible, request an alternate location that will not be a concern for these issues.

Ductile Iron Industry Mechanical Property Standards – Industry-standard Ultimate Tensile Strength, Yield Strength, and Elongation requirements are specified in SAE J434, ASTM A536, EN 1563, JIS G 5502, and

ISO 1083. There are some differences in the metal grades and minimum requirements specified, but they serve as a broadly accepted foundation that, for the most part, is firmly in line with practical foundry experience. Compare the customer's requirements against these standards. If the customer's requirements are out of line (and are not acceptable to the foundry) present the recognized standards to the customer and identify the requirements that are out of line with industrial norms. If necessary, explain the basic physics of the material – as strength increases, ductility decreases – and provide historical support from the literature (for example, www.ductile.org/didata/Section3/Figures/pfig3_1.htm, or other similar charts from the Ductile Iron Data section of the DIS website). If the customer requirements are in line with recognized standards, proceed to the next step.

A note on SAE standards – the old stand-bys of D4018, D4512, D5506, and D7003, specified in the June 1986 version of SAE J434, have been replaced in the updated February 2004 version. The JUN86 version specified BHN ranges and recommended typical (though not required) mechanical properties; this spec was very favorable to foundries. The FEB2004 version specifies minimum mechanical properties and recommends BHN ranges. This key difference has the effect of eliminating some of the old stand-bys and replacing them with additional metal grades with more achievable minimums. However, it is worthwhile to note that these minimums are experiential and not based on statistical capability.

Assessing Statistical Capability for Mechanical Properties – But, following AIAG, showing statistical capability (Cpk) is the goal. So, begin with the customer requirements for UTS, YS, and %E. Using a similar casting (comparable requirements, geometry, section size, gating configuration) with which the foundry has a representative history, calculate the foundry's statistical capability for each requirement. If the foundry does not have a similar casting, a casting with the same or similar metal grade can be substituted in the analysis.

Note that, for mechanical properties, one-sided capability calculations are required, because these properties typically have only minimum requirements. As a result Cpk = CpL (for additional explanation, refer to the SPC manual at www.aiag.org).

Some will argue that statistical capability is not a reasonable metric for casting mechanical properties, as casting mechanical properties data are non-normal or because casting mechanical properties do not represent an SPC-verified "stable, in-control" process. From a purely statistical standpoint, this is true. However, a customer who follows AIAG will expect some statement of statistical capability. Given that expectation, how should a foundry proceed?

To correct for non-normality in the data, there are several options. (Some of the key options are outlined here; for additional information, refer to the SPC manual at www.aiag.org.) One option: the data can be transformed using a Box-Cox transformation (a y^x transform by which the values (y) are raised to a power (x where x typically includes ±0.5, ±2, ±3, ±4, ±5); run a normality check on each set of transformed data, looking for the transform that will take the non-normal data and make it normal; a log x transform can also be used if this transform makes the data normal). Another option: the non-normal data can be analyzed using Weibul statistics (Weibul ++ is a software package that readily performs this analysis). The weakness to using Box-Cox or Weibul is that they can be confusing to the user unless he or she has had some statistical training. Perhaps more importantly, unless the customer has had some statistical training, it is very difficult to explain these statistical gyrations in a way that will give the customer confidence and the foundry credibility. So, unless the foundry is willing to take on the foundry AND statistical education of its customer, an alternate approach may be more advisable.

Even though it isn't technically correct from a rigorous, statistical standpoint, run the data through a typical capability analysis. See what the results show. Typical capability requirements are short-term capability of 1.67 and long-term capability of 1.33. However, many foundries have a difficult time meeting those levels. One major automotive foundry followed a recommendation from an automotive OEM black belt: for castings, shoot for a long-term capability of 1.00. Following this guideline, the foundry has shown a success rate of more than 99.5%, and, in most cases, this success rate has been acceptable to the foundry's customers.

Another means for presenting the foundry's capability is to reverse the capability calculation to determine what mechanical property limits the foundry is capable of meeting at a Cpk of 1.33 or 1.67.

For example, a foundry wants to calculate yield strength capability limits for a D4512 grade. Minimum yield strength is 45,000psi. Average performance on a similar job is 47,000psi with a standard deviation of 1,000psi. Cpk for yield strength is

$$\text{Cpk} = \frac{\text{average} - \text{LSL}}{3*\sigma}$$

$$= \frac{47{,}000 - 45{,}000}{3*1{,}000}$$

$$= 0.67$$

To back calculate a capability limit for Cpk > 1.33, based on this performance,

$$\text{Cpk} = \frac{\text{average} - \text{LSL}}{3*\sigma}$$

$$\text{LSL} = \text{average} - \text{Cpk}*3*\sigma$$

$$= 47{,}000 - 1.33*3*1000$$

$$= 43{,}010\text{psi}$$

So, if the customer requires a Cpk > 1.33 for yield strength of 45,000psi minimum, based on the foundry's historical performance, it is not capable of meeting this requirement. However, if the customer moved the minimum yield strength requirement to 43,010psi or less, the foundry would be capable.

Benefits of the Statistical Capability Approach – The key factor in this approach is to present this capability analysis to customers up-front, during initial APQP discussion or earlier, as possible. Doing so achieves a number of benefits:

1. Demonstrates that the foundry has a real understanding of its process and capabilities
2. Demonstrates that the foundry has a real understanding of the customer's requirements
3. Establishes a real understanding of actual foundry capability for the customer
4. Communicates a data-driven objective that the foundry can realistically achieve
5. Establishes a data-driven approach in discussions between the customer and the foundry
6. Documents an understanding that the foundry will have some fall-out, unless capability is shown

As noted previously, mechanical properties requirements are the place to start when reviewing a customer's spec, as they are usually the designer's primary concern. However, customers often place additional requirements on parts and castings. When addressing these additional requirements, the overall approach is the same as that outlined for mechanical properties: 1) assess the customer's requirements in the context of the test bar type, location (if sectioned from the casting), and industry standards; 2) assess the foundry's capability of meeting those requirements; 3) present these capability assessments to the customer; and 4) highlight all met capabilities, point out any capability shortfalls, and, as necessary, recommend capability limits.

Additional points to consider on each of the other requirements are discussed below.

Hardness

Hardness is strongly related to mechanical properties, increasing as strength increases and ductility decreases. This relationship is well established in the literature and by industry standards, but customers often request alternate (sometimes narrower, sometimes lower, sometimes both) hardness ranges, frequently as a response to machinability concerns. Sometimes, when alternate hardness ranges are mismatched to the established mechanical properties ranges, it may be difficult for the foundry to show capability of meeting both mechanical properties and hardness.

Brinell Test Locations – When approaching the customer's hardness requirements, the same considerations should be made for hardness test location as for casting section tensile bar locations, including section size, solidification rate, and cooling rate, in the hardness test location.

Ductile Iron Industry Hardness Standards – Review the industry standards (SAE J434, EN 1563, and JIS G 5502; ASTM A536 does not specify hardness) and verify that the hardness range requested by the customer is reasonable in both range and target. If the customer's requirements are out of line (and are not acceptable to the foundry) present the recognized standards to the customer and identify the requirements that are out of line with industrial norms. If necessary, explain the fundamental relationship between hardness, strength, and elongation, and provide historical support from the literature (for example, www.ductile.org/didata/Section3/Figures/pfig3_6.htm, or other similar charts from the Ductile Iron Data section of the DIS website). If the customer requirements are in line with recognized standards, proceed to the next step.

Assessing Statistical Capability for Hardness – The approach to assessing hardness capability is similar to the approach outlined for mechanical properties. One key difference is that hardness specifications tend to be two-sided (that is, they have a minimum and a maximum); therefore, Cpk is equal to CpL or CpU, whichever is smaller (for additional explanation, refer to the SPC manual at www.aiag.org).

Because brinell hardness data tends to be discrete (when diameter is measured in 0.1mm increments), calculation of capability can be problematic. When the data is discrete, a true measure of standard deviation is difficult to obtain. As outlined for mechanical property testing, the foundry can use more advanced statistical techniques to address the discreteness, or can simply calculate the Cpk, using the formula in the AIAG SPC book, and use the value as an index for guidance. If the data is continuous (when diameter is measured in 0.01mm increments), these issues of discreteness do not enter the calculations, and the results can be assessed as previously outlined. Whether discrete or continuous, the same guidelines for acceptable Cpk > 1.00 and for proposing alternate capability limits (when the actual data shows Cpk < 1.00 against the original customer requirements), apply for hardness as for mechanical properties.

When the customer's hardness ranges do not follow the industry standard hardness ranges for the required mechanical properties, the foundry may have difficulty in showing capability for both mechanical properties and hardness. If the casting is capable of meeting the mechanical properties requirements, there is a good chance that the casting hardness is centered in the typical, industry standard hardness range, resulting in a Cpk > 1.00. However, if the customer changes the hardness requirement away from industry standard, there is a good chance that the casting's hardness will not be centered in the customer's range, resulting in a reduced Cpk. (For further discussion of Cpk and the effect of off-target distributions, refer to the SPC manual at www.aiag.org.) If the customer will accept this reduced Cpk, they must also accept the increased probability of receiving castings with out-of-range hardness. If this is not acceptable to the customer, then the hardness range must be changed, the mechanical properties requirements must be changed, or lower mechanical property capability must be accepted (along with the increased probability of receiving castings with out-of-range mechanical properties).

Impact properties

Like hardness, impact properties are strongly related to mechanical properties, with impact properties directly proportional to elongation and inversely proportional to strength and hardness. As with hardness, this relationship is well documented in the literature and in industry standards, but customers sometimes request improved impact properties to meet functionality requirements.

Casting Section Impact Test Bar Locations – The same considerations should be made for impact test bars as for tensile bars locations, including keel/Y block vs. casting section, and, if the test bar comes from the casting, section size, solidification rate, and cooling rate, in the impact test bar location. These considerations are particularly critical in impact test bars, as the impact test (especially at low temperatures) is extremely sensitive to flaws.

Ductile Iron Industry Impact Properties Standards – EN 1563, JIS G 5502, and ISO 1083, all provide specifications for impact resistance. SAE J434 FEB04 provides typical results for various metal grades. The minimum values, test temperatures, and notch geometries are different from one standard to the next, so it is important that the foundry carefully review the relevant specification. Despite these well-established standards, some customers produce alternate specs for impact property tests, varying the minimum values, test temperatures, and notch geometries. If the customer's impact property requirements are out of line with the existing standards, it is strongly advisable that the foundry works with the customer to bring them back in line. Given the sensitive nature of the impact test (especially at low temperatures), a foundry can struggle with unrealistic impact test requirements for the life of the casting, particularly if capability is required for mechanical properties and impact properties.

One difference between the standards for impact properties and the standards for mechanical properties and hardness is that the impact properties standards require that three bars be tested per test, that all three values exceed a minimum value, and that the average of the three values exceed a minimum value. This method for specifying impact properties acknowledges the sensitive nature of the impact test.

Assessing Statistical Capability for Impact Properties – Because minimum and minimum average impact properties are specified in the standards, the approach to assessing the statistical capability of impact properties is slightly different than the approach for assessing statistical capability of mechanical properties and hardness.

Like mechanical properties, the specifications are one-sided, so Cpk = CpL. Unlike mechanical properties, impact properties must meet both minimum and minimum average requirements. To calculate capability against the minimum requirement, take the results of all of the individual tests and calculate CpL. To calculate capability against the minimum average requirement, take the average values from each test and use those values to calculate CpL.

For example, a foundry conducts ten low-temperature impact properties tests on a D4018 material; the results were as follows:

Test	**Bar 1 Result (J)**	**Bar 2 Result (J)**	**Bar 3 Result (J)**	**Average Result (J)**
1	13	17	17	16
2	14	16	17	16
3	15	15	17	16
4	14	9	17	13
5	13	15	14	14
6	16	12	14	14
7	12	15	16	14
8	11	15	15	14
9	11	11	14	12
10	13	15	13	14

Calculate capability against minimum

$$\text{Cpk} = \frac{\text{average} - \text{LSL}}{3*\sigma}$$

Average all individual values:

$$\text{Average} = \frac{13+17+17+14+\ldots+14+13+15+13}{30}$$

$$= 14$$

Calculate capability against minimum average

$$\text{Cpk} = \frac{\text{average} - \text{LSL}}{3*\sigma}$$

Average the bar averages:

$$\text{Average} = \frac{16+16+16+\ldots+14+12+14}{10}$$

$$= 14$$

LSL = 9J

Calculate σ of all individual values:
$\sigma = 2.1$

$$Cpk = \frac{14 - 9}{3*2.1}$$

$$= 0.79$$

LSL = 12J

Calculate σ of the average values:
$\sigma = 1.2$

$$Cpk = \frac{14 - 12}{3*1.2}$$

$$= 0.56$$

Ferrite/Pearlite Ratio

In a sound casting with acceptable nodularity and no carbides, the ferrite/pearlite ratio (or matrix microstructure) is a primary determiner of mechanical properties, hardness, and impact properties of the material. Generally, as ferrite % increases, strength and hardness decrease, and ductility and impact properties increase. As with the other properties already discussed, the relationship between matrix microstructure and properties is well known (reference http://www.ductile.org/didata/Section3/Figures/pfig3_15.htm and http://www.ductile.org/didata/Section3/Figures/pfig3_41.htm, or other similar charts from the Ductile Iron Data section of the DIS website). However, customers sometimes specify ferrite/pearlite ratio requirements for machinability reasons, based on experiences that suggest that increased pearlite content and fine pearlite degrade machinability. If these additional microstructural requirements mismatch with the other requirements (mechanical properties, hardness, impact properties), foundries may have difficulty showing capability against all requirements.

Matrix Microstructure Test Locations – When approaching the customer's matrix microstructure requirements, the same considerations should be made for microstructure test location as for casting section tensile bar locations, including section size, solidification rate, and cooling rate, in the microstructure test location.

Ductile Iron Industry Matrix Microstructure Standards – Unlike the other properties already reviewed, the main governing industry standards for ductile iron do not include specific requirements for matrix microstructure. SAE J434, EN 1563, JIS G 5502, and ISO 1083, all provide callouts for typical or reference matrix microstructure (ASTM A536 does not contain any matrix microstructure callouts), but they are broad: ferrite, ferrite-pearlite, pearlite-ferrite, pearlite, pearlite or tempered martensite, tempered martensite, or bainite-ausferrite. Because these are designated as typical or reference, there are no requirements in these specifications.

One reason that microstructural requirements are not specified in the standards is that a broad range of microstructures is possible for a given set of properties. While matrix microstructure is a primary determiner of mechanical properties, hardness, and impact properties of the material, the way that this microstructure is achieved can also affect these properties. For example, high silicon levels can strengthen ferrite and produce higher hardness, higher strength, lower ductility, and lower impact properties, at the same ferrite %; the amount of copper and tin that are used to achieve a particular level of pearlite can vary the strength and hardness of the pearlite. When customers place microstructural requirements in their specifications, they can limit the range of tools that a foundry can use to achieve the mechanical property requirements (the designer's real intent), and drive unnecessary costs into the foundry's operation.

A second reason that microstructural requirements are not specified in the standards is a lack of standards for determining ferrite/pearlite ratio. Some image analysis and manual determination techniques exist, but these are not standardized. Typical references that can be used as guidelines for microstructural determination – and can be provided to customers who insist on microstructural requirements – include the AFS Ductile Iron Microstructures Rating Chart, the AFS Reference Microstructures for Measurement of Pearlite and Ferrite Content in Ductile Iron Microstructures, and the AFS Foundrymen's Guide to Ductile Iron Microstructures. The method of ferrite/pearlite ratio determination, and the precision of that measurement (for example, its Gauge R&R), can affect the method for assessing the foundry's capability of meeting the requirement.

Assessing Statistical Capability for Ferrite/Pearlite Ratio – The same approaches already outlined can be used to assessing its capability for matrix microstructure. Sometimes the customer's specification is one-sided (for example, 40% max pearlite) and Cpk = CpL (similar to mechanical properties and impact properties); sometimes the customer's specification is two-sided (for example, 20-80% pearlite) and Cpk is the minimum of CpU and CpL (similar to hardness). Depending on the measurement technique, discrete (like hardness measurements to 0.1mm increments) or continuous (like mechanical properties, impact properties) data can be collected and used for capability assessment, as outlined previously.

As with hardness and impact properties, matrix microstructure is linked to mechanical properties. As a result, if a customer specification requires a tight range on matrix microstructure, this could jeopardize the ability of the casting to meet the mechanical property requirements. This can be borne out by assessing the capability of the casting to meet both sets of specifications. For example, if a customer requires that a casting meet a minimum 45,000psi yield strength, the foundry might normally make that casting with 25-45% pearlite. If the customer then adds a 30% max pearlite requirement, the foundry might now have a real pearlite operating range of 25-30% pearlite. This would be a difficult range for any foundry to maintain in a production setting. So the foundry is faced with a choice: if the foundry targets its process to be capable of meeting the pearlite requirement, the foundry might increase its probability of making castings that fail mechanical properties requirements; if the foundry targets its process to show capability on mechanical properties, it may increase its probability of exceeding the pearlite restriction.

If this problem is identified during APQP, the foundry can provide the customer with real data from similar parts and pass the choice back to the customer. To achieve a particular metal grade, a foundry needs a particular range of pearlite. This is a matter of physics, has been well demonstrated in the literature, and is the experience of most foundries. To prove this to a customer, begin with a job that shows mechanical properties statistical capability, then measure the microstructure of those castings, and back-calculate the limits required to achieve capability on matrix microstructure. With this information in hand, the foundry can put the choice to the customer:

1. The foundry can achieve statistical capability on mechanical properties if the microstructural requirements are changed to the foundry's recommendations…and meet both requirements consistently, over time.
2. If the microstructural requirements are not changed, the foundry can target and control its process to achieve statistical capability on microstructure and lose capability on mechanical properties…and fail mechanical properties requirements at some frequency.
3. If the microstructural requirements are not changed, the foundry can target and control its process to balance the capability of mechanical properties and matrix microstructure…and fail both requirements at some frequency.

Though ferrite/pearlite ratio can affect the machinability of the casting – and therefore the variable costs, in tool wear, tool change-out, etc. – mechanical properties are typically more important to part function than matrix microstructure. Additionally, the foundry can argue that there are other factors that the foundry can control to greater effect on machinability (reference DIS Hot Topic #3, 2000) than a small change in ferrite/pearlite ratio.

Nodularity (Nodularity %, Size, Count)

Nodularity is another factor that affects mechanical properties, hardness, and impact properties: strength, ductility, hardness, and impact properties all improve as nodularity improves. As with the other properties already discussed, the effect of nodularity on properties is well known (reference http://www.ductile.org/didata/Section3/Figures/pfig3_11.htm and http://www.ductile.org/didata/Section3/Figures/pfig3_45.htm, or other similar charts from the Ductile Iron Data section of the DIS website).

Industry and customer specifications typically include a minimum nodularity %, but customer specifications sometimes also include requirements on size and count. The nodularity requirements exist because of the important relationship between nodularity and properties, and, in some cases, customers add additional requirements because they have related poor surface finish to excessive nodule size or insufficient nodule count. To assess nodularity %, foundries can use a correlation between UT velocity and nodularity % obtained through microstructural analysis, or they can use microstructural analysis; to assess nodule size or count, foundries are restricted to using microstructural analysis.

Nodularity Test Locations – Nodularity analyses can be done directly on the castings or on coupons poured from the melt used to pour the castings. If the nodularity assessment is made from coupons, care must be taken in producing those coupons to make sure that they reflect the nodularity in the casting. Furthermore, if the nodularity test piece is taken from the casting or if the casting is UTed to assess nodularity, the same considerations should be made for test location as for casting section tensile bar locations, including section size and solidification rate in the test location.

Ductile Iron Industry Nodularity Standards – A detailed discussion of rating nodularity in ductile iron, including the relevant standards, can be found in DIS Hot Topic #1, 2005. ASTM A247 and ISO 945 provide the primary guidance for nodularity measurement, minimum nodularity %, nodule shape, and nodule size. Work continues on developing objective image analysis standards for nodularity rating, and many foundries have already adopted image analysis for nodularity analysis; however, the current accepted standard for rating nodularity % and nodule count is the DIS Graphite Rating in Ductile Iron wall chart (this chart is referenced SAE J434).

A typical minimum nodularity % requirement is 80% conforming to Types I and II (per ASTM A247). This is reasonable for most foundries. Customers sometimes require higher levels of nodularity, especially in highly stressed applications. Size and count are sometimes specified; these are generally inversely related – as size decreases, count increases, and vice versa. As a result, it should not be necessary to specify both size and count.

Assessing Statistical Capability for Ferrite/Pearlite Ratio – Nodularity % is a one-sided specification (Cpk = CpL); size and count specifications can be one-sided (Cpk = CpL) or two-sided (Cpk = minimum of CpU and CpL). As with ferrite/pearlite %, the method of nodularity evaluation, and the precision of that measurement (for example, its Gauge R&R), can affect the method for assessing the foundry's capability of meeting the requirement. If image analysis is used, or if the inspector interpolates between the guidelines shown on the DIS wall chart, continuous data is available for standard capability analysis – follow the procedures outlined previously. If the data is not continuous (rated to the closest 5% or 10% or rated on a discrete scale), follow the recommendations for discrete hardness data.

The primary consideration with addressing nodularity specifications is assessing the capability of the foundry to meet the requirements, based on historical performance. Unlike the mismatches that sometimes occur in customer specs between mechanical properties and hardness, impact properties, and ferrite/pearlite ratio, foundries should work to meet a reasonable nodularity % specification, to help ensure all properties are met. Additional nodularity requirements can be assessed based on the foundry's history.

A last point on nodularity: 100% UT inspection of castings. This is an old requirement, originating in the past when ductile iron was new and foundries did not have adequate controls to ensure good nodularity. Now, this requirement can drive labor, equipment, and cost into a foundry's operation. Additionally, because nodularity is so critical to the performance of ductile iron castings, foundries should work to ensure good nodularity through rigorous metallurgical and pouring process controls rather than inspect for poor nodularity at the end of the process. Foundries with adequate controls should have an established record of producing castings with acceptable nodularity. Look at a foundry's historical performance. How many nodularity failures has the foundry had over the number of castings made? Is this failure rate < 3ppm (parts per million)? Processes with a fall-out rate of < 3ppm have Cpk > 2; in other words, they are "six sigma" processes. This means that the foundry has adequate process controls that ensure a long-term ability to make parts that exceed nodularity requirements and that these controls and this performance justify the elimination of 100% UT end-of-line inspection. Now, some would argue that the risks involved with passing of a casting with bad nodularity are high enough that they justify 100% inspection and the associated costs. But would a foundry tolerate the costs associated with a 100% hardness inspection requirement if their fall-out rate was less than 3 parts per million? No – this unnecessary, costly inspection would not be tolerated. Further, if a foundry experiences less than a 3ppm failure rate for nodularity and this is not enough to justify elimination of the inspection, what level of performance would justify the elimination? Less than 1 part in ten million? 1 part in fifty million? At some point, demonstrated performance should ameliorate the risk.

As customers pursue lower-cost castings from overseas competitors and pressure current suppliers for cost reductions, foundries need to look for opportunities to remove non-value-added work from their operations. The elimination of non-value-added UT could be a major opportunity for foundries with the proper process controls and demonstrated long-term performance. It would be a competitive advantage for these foundries and a reflection of the higher quality processes that the foundry can offer its customers.

Carbides/chill (%, Depth)

Primary carbides, or chill, are still another factor that affect mechanical properties, hardness, and impact properties: tensile strength, ductility, and impact properties all decrease with the presence of carbides; yield strength and hardness can increase (these statements apply to standard ductile iron grades and do not necessarily apply to specialty grades like Ni-resist or HiSilMoly). The effect of carbides on properties is well known (reference http://www.ductile.org/didata/Section3/Figures/pfig3_12.htm and http://www.ductile.org/didata/Section3/Figures/pfig3_13.htm or other similar charts from the Ductile Iron Data section of the DIS website).

% carbides is the amount of microstructure that is primary carbide or chill. Depth is the linear distance perpendicular to the surface of the casting that carbides extend into the casting.

Industry and customer specifications typically include a requirement aimed at minimizing the amount of carbides in the casting microstructure. The carbide requirements exist because of the effect that carbides have on reducing ductility and dramatically increasing hardness, the former affecting part performance and the latter affecting part machinability. To assess carbide %, foundries have a number of options, each with certain limitations

1. UT / eddy current velocity can detect massive carbides – 40% carbides by volume or more; determines % but not depth
2. Hardness (small indenter: Rockwell) can detect massive carbides – 30% carbides by volume or more; determines % and depth (resolution limited by indentation diameter and spacing between sequential indentations)
3. Microstructural analysis can detect carbides at any level; determines % and depth; however, this approach requires sectioning and destruction of the casting

Carbide Test Locations – Carbides tend to appear in locations that solidify very rapidly: sharp or small diameter external corners, isolated thin sections, at the ends of long runs of iron, at parting lines with heavy flash, or in last regions to fill. While carbide tendency in the iron can also be assessed using thermal analysis or chill wedges, these are outside the scope of this discussion.

Ductile Iron Industry Carbide Standards – The primary industry standards do not include a detailed discussion of carbide requirements (SAE J434 contains a statement prohibiting the presence of detrimental primary cementite). References that can be used as a guideline for rating carbide % is the AFS Reference Microstructures for Visual Estimation of Iron Carbide Content In Nodular Iron and the AFS Foundrymen's Guide to Ductile Iron Microstructures.

Assessing Statistical Capability for Carbides – Carbide % is a one-sided specification (Cpk = CpU). As with the other microstructural requirements, the method of carbide evaluation, and the precision of that measurement (for example, its Gauge R&R), can affect the method for assessing the foundry's capability of meeting the requirement. If image analysis is used, or if the inspector interpolates between the guidelines shown on the references, continuous data is available for standard capability analysis – follow the procedures outlined previously. If the data is not continuous (rated to the closest 3%, for example, or rated on a discrete scale), follow the recommendations for discrete hardness data.

The primary consideration with addressing carbide specifications is assessing the capability of the foundry to meet the requirements, based on historical performance. Unlike the mismatches that sometimes occur in customer specs between mechanical properties and hardness, impact properties, and ferrite/pearlite ratio, foundries should work to meet a reasonable carbides % specification, to help ensure all properties are met. Additional carbide requirements can be assessed based on the foundry's history.

As with nodularity, for foundries with adequate process controls and with a demonstrated record of making carbide-free castings, 100% carbide inspection is an unnecessary, non-value added operation. As with nodularity, the presence of carbides can be very detrimental to the performance of ductile iron castings; therefore, foundries should work prevent carbides through pouring process controls rather than working to inspect for carbides at the end of the process. Again, if a foundry's process has a fall-out rate of < 3ppm, it is a "six sigma" processes, and should be able to justify the elimination of 100% inspection. This is another example of a potential cost savings – the elimination of non-value-added inspection for foundries with the proper process controls and demonstrated long-term performance.

Chemistry (C, Si, Mg, Cu, Mn, CE, AF, etc.)

Iron chemistry is one of the primary sets of casting variables that foundries use to control all of the properties already discussed. The relationships of each of the major alloying elements with each of the properties discussed have been well documented in the literature.

Ductile Iron Industry Chemistry Standards – Typical chemical compositions for some of the major alloying elements are called out in SAE J434, JIS G 5502, and ISO 1083. However, these ranges are not specifications, they are for information only. As a result, there are no chemistry requirements called out in the primary ductile iron standards.

Some customer specifications contain chemistry requirements. Customers set these specifications to ensure 1) that the foundry's process has chemistry controls, 2) that the foundry's process is as common as possible with other foundries, and 3) that parts made by different foundries will have common properties and machinability. These requirements are sometimes based on the typical chemistries called out in the industry standards which are then modified based on experiences with current or previous casting suppliers. As a result, these ranges may reflect a particular melting or treatment process, a particular raw material supply, or a particular alloying practice at a particular foundry. This drive to commonize overlooks that fact that different foundries can achieve the same material by following very different processing paths, and, in some cases, differences between foundries necessitate different chemistry ranges (for example, cupola melt versus electric melt).

Assessing Statistical Capability for Chemistry – When a foundry is confronted with a chemistry range that will be difficult for their process to meet, the foundry can present the different-foundry-equals-different chemistry argument to the customer and request a deviation to the specification. If the customer does not readily accept this argument, the foundry can reconstruct the argument and support it using statistical capability analyses.

To do so, the foundry can follow the same procedure outlined for mechanical properties.

1. Select an existing casting that has a similar chemistry to the new casting
2. Collect the chemistry data for that casting and assess the statistical capability for each element called out in the customer's specification
3. Identify elements with acceptable capability and accept the customer's limits on those elements
4. For elements with unacceptable capability, calculate new capability limits that the foundry can accept and propose these to the customer

To be clear, chemistry ranges are reasonable requirements for a customer to include in a specification. In fact, they may actually benefit the foundry in the long term: these ranges can force the foundry to implement improved methods for chemistry control, thereby improving quality and reducing costs. This continuous improvement may be the customer's underlying motivation for putting chemistry requirements into their specifications. However, as with the other properties and requirements already discussed, chemistry requirements must be matched with the other properties and especially with the foundry's process. Statistical capability can be the way that a foundry shows its willingness to accept the call for improved quality while conveying an understanding of its process and of its cost constraints.

PV Testing

In production validation (PV) testing, a casting is tested under conditions that mimic actual operation. Because this kind of testing is extremely product-specific, there are no industry standards governing it. Additionally, due to the expense of the testing, a foundry is unlikely to have enough data to complete a satisfactory statistical capability study. As a result, the approaches outlined above will be of limited value in addressing PV requirements. The foundry is left to rely on its experience with previous, similar parts.

Heat Treatment

Heat treatment is included in customer specifications for a variety of reasons, from annealing heat treatments designed to maximize ductility or relieve stress or improve machinabiltiy, to normalizing heat treatments designed to homogenize and prepare a casting for induction heat treatment, to strengthening heat treatments like Q&T or austempering, to salvage heat treatments seeking to correct improper casting processing. In some cases, the heat treatment requirements have been carried along from previous designs and the reasons for heat treatment are not known.

There are no industry standards governing heat treatment, but most of the primary standards include a statement indicating that heat treatment is allowed upon agreement between supplier and customer. Because heat treatment is generally used to modify one of the properties outlined above, foundries can use the techniques outlined above to determine whether or not heat treatment is required, by assessing the impact of the heat treatment on the capability of each of the properties of interest. In some cases, a foundry may be able to use statistical capability to show that, for example, an annealing heat treatment may not be required because the foundry's process is capable of producing castings that meet the customer's requirements in an as-cast state.