

Offsetting Shrinkage in Ductile Iron What Thermal Analysis Shows

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Abstract

The natural shrinkage that occurs during the solidification of Ductile Iron can be offset by the expansion caused by the formation of graphite. Though this has been known for some time, thermal analysis has some interesting contributions to understanding exactly what is going on, and offers some opportunities for better control of late graphite expansion in moderate section sizes. Different modes of solidification are examined and measured, and the early and late graphite content are calculated using thermal analysis. Carbon flotation is seen as a fourth form of solidification that is both hypereutectic and hypoeutectic. Shrinkage is seen as a lack of late graphite growth needed to offset the natural contraction of the Ferrite. Grain boundary shrinkage can be seen as an escape mechanism for minor unfulfilled contraction. Stress relief heat treat increases the graphite volume thereby collapsing any remaining of the grain boundary shrinkage and improving fatigue life and other physical properties.

Introduction to Shrinkage and Expansion

Ductile Iron consists of primarily two materials: a steel matrix surrounding graphitic nodules. The steel matrix can be ferritic, pearlitic or martensitic, or a combination of any two. The majority of ductile castings are generally ferritic with less than 10% pearlite. A small amount of retained austenite is generally present and, in combination with micro carbides, retains about 20% of the carbon¹. This carbon can then be transformed into graphite during heat-treating.

The steel matrix will shrink considerably when cooling from 2000 degrees to room temperature. Offsetting this is the transformation of dissolved carbon into nodules of graphite, which occupies 9 to 11% more volume as graphite than as carbon.

One insidious form of shrinkage is a suck-in. It is caused by the same factors as shrinkage, but shows no internal porosity as the volume loss is transferred to the surface of the casting. Suck-ins are caused by the combination of a high shrinkage iron, and a thin or weak casting wall that cannot resist the internal pull. This could be due to a combination of a casting designed hot spot and/or hotter than normal iron. Eutectic and hypereutectic irons are more susceptible to suck-in than hypoeutectic iron because they are slow to form thick walls. All though these castings might not show internal shrinkage, they should be counted as having shrinkage nonetheless.

Two other forms of voids appear in iron: micro-shrinkage, and gas or blows. Gas is caused by Nitrogen and Hydrogen being present in the iron⁹, but is not a true shrinkage, though some people mistake it for shrinkage.

The micro-shrinkage appears in the grain boundaries^{5 10 11} as the final solidification takes place, and can be caused by micro-segregation where the grain boundaries become enriched in low melting elements and phases⁸. Another possible cause of grain boundary shrinkage can be just the internal stress in the casting caused by not having macro-shrinkage. Macro-shrinkage relieves the shrinkage-induced stress of the casting and reduces the endothermic signature of the end of freezing arrest. So when macro-shrinkage is avoided, the remaining unfulfilled shrinkage is transferred to the grain boundaries.

Grain-boundary shrinkage may be preferred over macro-shrinkage, but these voids could also contribute to reducing fatigue life. Fortunately, heat-treating allows dissolved carbon (occupying no volume in the casting) to move to the graphite nodules where it adds to the volume of graphite. This graphite growth increases expansion forces, and helps collapse the grain boundary voids, and improves fatigue life.

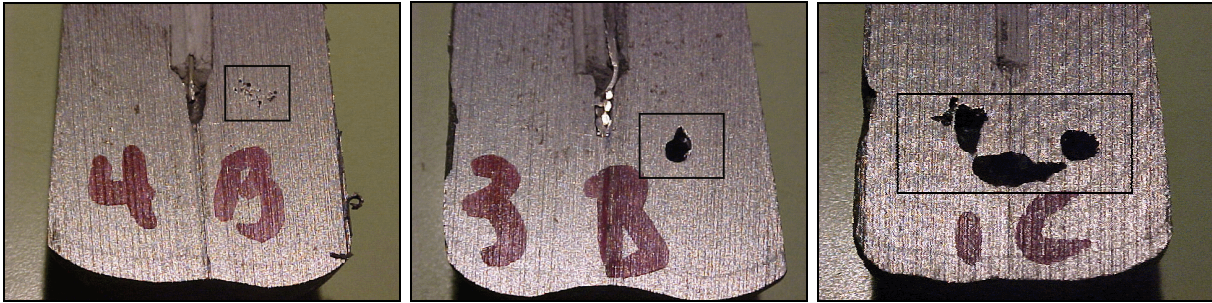


Figure 1. These are three examples of different levels of macro-shrinkage in thermal analysis cups. Shrinkage occurs at the point of the last metal to solidify, so is located around the thermal couple for easy detection. Some suck-in occurred in the right and middle sample.

Literature Review

Skaland and Grong¹ suggest that up to 20% of the carbon in iron does not transform to graphite or pearlite, but is tied up as micro partials of carbides that only convert to graphite on heat treating. They base this on the results of studies of heat-treating, which increases both the total graphite and the nodule count. This suggests that 10 to 20% of the carbon present must be discounted, as it will not form graphite during solidification.

Heine³ suggests that higher nodule counts lead to less shrinkage, but that above about 4.70 C.E., carbon floatation sets in, and then the nodule counts will vary greatly from the depleted zone to the flotation zone. He also reported two Liquidus arrests in strongly hypereutectic irons⁴.

Stefanescu et al⁵ suggest that shrinkage be broken down into macro-shrinkage caused by feeding problems, micro-shrinkage caused by contraction of the solid metal, and by micro-porosity caused by gas evolution within the iron. In this paper, we will use Stefanescu's definitions of shrinkage and examine what can be done to minimize macro-shrinkage. We will also show that macro-shrinkage can be caused not only by gating problems, but also by high carbons.

Graphite Growth in Solidifying Iron

Graphite is a hexagonal-closepack form of carbon that can grow in both the liquid and solid forms of iron. In theory, in irons above the eutectic composition of carbon, the graphite first nucleates in the liquid, and then continues to grow in the solid. In irons below the eutectic composition, the graphite does not start to grow until the iron reaches eutectic temperature. As seen in a micro, the

larger nodules are from growth initiated in the liquid, and the smaller nodules are from growth that does not start until solidification temperatures are reached. During heat-treating, the existing nodules increase in size, and very small nodules appear¹.

The graphite nodules that form in the liquid in hypereutectic irons continue to grow as the iron cools, so the amount of growth that occurs in the liquid is smaller than what would be assumed by examining the micro.

The expansion from the graphite that grows in the liquid, generally pushes liquid back into the riser or down sprue, and does not offset shrinkage. This is because hypereutectic irons do not form thick walls before the eutectic temperature is reached, and of course, there are no dendrites to block this reverse feeding. If the gates have frozen off with a hyper eutectic iron due to design, then hypereutectic graphite expansion could cause mold wall movement.

Late graphite is defined as graphite that grows during or after the eutectic solidification. This late graphite can exert internal pressure to offset the shrinkage we would like to prevent. The graphite continues to grow in size as the casting cools, until a balance is reached between the expansion pressure caused by adding more carbon to the graphite nodule and the stress induced in the surrounding matrix by the expanding nodule. At high temperatures, the matrix is soft and flexible and the graphite grows freely. At low temperatures the matrix stiffens, and exerts a counter pressure on the graphite nodule. Heat treating relaxes the matrix and allows graphite growth to resume, and hopefully to go to completion.

In order to minimize shrinkage, it is necessary to maximize the formation of late graphite without having to reduce the actual amount of graphite. Understanding what happens in a non-steady state solidification of Ductile Iron suggests a few ways that this can be done.

In a hypoeutectic mode of solidification, austenite forms as a solid with a lower than average carbon content. This increases the carbon content of the remaining liquid until it reaches the eutectic composition. Likewise, in a hypereutectic mode of solidification, graphite nodules form in the liquid, removing carbon from the liquid until it is reduced to the eutectic composition

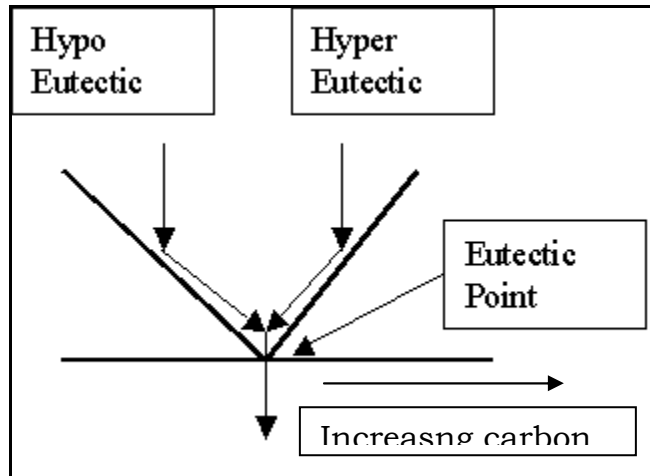


Figure 2. Phase diagram showing movement of carbon concentration in liquid metal as iron solidifies.

It would seem from figure 2 that the maximum amount of carbon that can be formed in late graphite is determined by the eutectic composition, and as long as the iron is at eutectic or above, the amount of late graphite will be the same. But there are some methods that can actually increase the amount of late graphite. The first is to reduce the silicon, the second is to reduce the pearlite, and the third is to run slightly hypereutectic and make use of magnesium's ability to suppress the formation of graphite. The first two methods will also significantly change the physical properties of the iron, so they may not be possible to implement. The third, which involves running a C.E. from 4.35 to 4.55, opens some possibilities.

Thermal Analysis shows how this third method works and how it actually decreases shrinkage. TA also shows the pitfalls of higher C.E.s and where adding more carbon may actually increase shrinkage.

Increasing Graphite to Avoid Shrinkage

Thermal analysis has shown that under dynamic conditions, the amount of late graphite can be increased considerably by using a hypereutectic chemistry between 4.33 and 4.60 that solidifies without a graphitic liquidus. In other words, below a certain C.E. value, the presence of Magnesium and possibly other elements in Ductile Iron, prevent graphite from forming in the liquid. So even though, on the phase diagram, we should see a graphitic liquidus, in practice there is no graphitic liquidus between a C.E. of 4.33 and about 4.60.

To actually benefit from this window, the C.E. should be slightly hypereutectic (4.4+) and safely away from a higher C.E. that would form a graphitic liquidus. Our research indicates that this point is about 4.6+, though it may change with section size and magnesium level. In addition, chemical analysis has some variation in its own accuracy, so care should be taken in establishing the exact maximum level for a given foundry's practice.

In qualifying curve types in thermal analysis, there are three basic shapes: One that shows an austenitic liquidus and a eutectic arrest, one that shows a graphitic liquidus and eutectic arrest, and one that only shows a eutectic arrest.

Surprisingly, the “eutectic only” mode is very common in iron used for small and medium size casings. When testing the chemistry for these “eutectic only” irons, it was found that the carbon equivalent varied from the eutectic composition of 4.33 all the way up to 4.58. The samples above 4.66 carbon equivalent generally show a graphite liquidus.

It is speculated that the magnesium and calcium is inhibiting the graphite liquidus up to about a 4.6 carbon equivalent. The amount of these elements in the iron may also have an effect on how much of a carbon equivalent can be suppressed¹. This means that an iron with a C.E. of 4.55 can behave as a eutectic iron but will add an additional 22 points of carbon to counteract the shrinkage. But an iron with a C.E. of 4.65 will behave not much differently than one of 4.33 C.E. in suppressing shrinkage.

C.E.	Silicon	Carbon	Graphite In Liquid	Late Graphite	Improvement Over Eutectic
4.20	2.40	3.40	0.00	2.72	- 3.5 %
4.25	2.40	3.45	0.00	2.76	- 2.1 %
4.30	2.40	3.50	0.00	2.80	- 1.1 %
4.33	2.40	3.53	0.00	2.82	Base Line
4.35	2.40	3.55	0.00	2.84	0.7 %
4.40	2.40	3.60	0.00	2.88	2.1 %
4.45	2.40	3.65	0.00	2.92	3.5 %
4.50	2.40	3.70	0.00	2.96	5.0 %
4.55	2.40	3.75	0.00	3.00	6.3 %
4.60	2.40	3.80	0.00	3.04	7.8 %
4.65	2.40	3.85	0.32	2.82	0 %
4.70	2.40	3.90	0.37	2.82	0 %

Figure 3. Assumptions: 20% carbon retained in matrix, no graphitic liquidus forms till above 4.60 C.E. Above 4.70 C.E. there is a risk of carbon flotation.

This would account for the frequency that eutectic freezing modes are found. The Eutectic is no longer just a point, but a small plateau from 4.33 to about 4.60 due to the presence of magnesium. This can result in an increase of 7.8% more carbon forming in the late solidification, or shrinkage being reduced by 0.8% of the total volume of the carbon. This also suggests that the amount of shrinkage in castings can vary considerably over a small carbon range, and

¹ Research on the effect of Magnesium on the eutectic undercooling suggests that the mechanism might be the level of oxygen in the iron and therefore the type and quantity of seed crystals present.

that a change from a C.E. of 4.55 to 4.65 will result in 0.8% volumetric shrinkage.

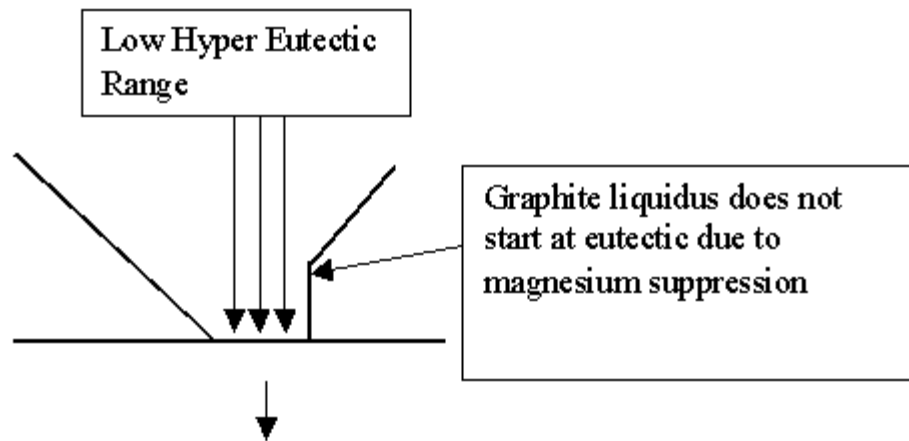


Figure 4. Expanded region of eutectic zone due to magnesium suppression of graphite formation.

Once the carbon equivalent becomes higher than the suppressed value, then the effect will be lost, the extra carbon will be removed by graphite formed in the liquid, and macro-shrinkage will increase.

This goes against the idea of counteracting shrinkage by simply increasing the carbon content. It suggests that it would be better to increase the carbon until the iron is slightly hypereutectic, but does not yet exhibit a graphitic liquidus.

Carbon Flotation in small castings

As the carbon content increases into the graphitic liquidus area, a stronger graphitic liquidus occurs that may not simply reduce the carbon content to eutectic, but may actually remove enough carbon to reduce the C.E. level below the eutectic. This results in an unusual thermal analysis curve that has both a graphitic liquidus and an austenite liquidus followed by the eutectic arrest. This then proves even further that increasing the carbon beyond the graphitic liquidus may drastically increase shrinkage.

Heine xxx and others have previously documented multiple arrests in their research, but these arrests were not identified as anything other than graphitic arrests⁴. This is the first time that multiple liquidus arrests have been identified in a single sample.

The dynamics of inoculation, magnesium, carbon content, and other alloys make a system that needs to be tightly controlled to supply the necessary amount of carbon and alloys and yet prevent a graphitic liquidus from increasing shrinkage and porosity.

Results

Samples were taken from many foundries in this research. Two are presented as demonstrating the interrelationships of freezing mode, shrinkage, late graphite and nodule count. The results are from the thermal analysis instrument using the same calibration for both foundries. While the readings are approximant, they are in agreement with the measurements of the foundries, i.e. the 77% nodularity was recorded as an 80%.

Table 1 and 2 show typical results from two different foundries having different chemistry aims and inoculation practices. The test data shows considerable interrelationship between shrinkage, and nodule count in the hypoeutectic irons, and in table 1, the shrinkage seems to be related to both nodule count, and the double arrest.

The Hypo-hypereutectic arrest in table 1 greatly reduced the available late graphite and increased the shrinkage. The nodule count relates well to the nodularity. This foundry would do well to reduce their carbon slightly and avoid hypereutectic freezing modes. Late graphite control would greatly benefit shrinkage in this foundry.

Mode	Nodularity	Nod Count	Late Graphite	Shrink	Undercooling
Eutectic	84	330	100	1	8
Hypoeutectic	86	330	86	0	5
Hypo-Hyper	93	380	69	12	9
Eutectic	85	380	100	6	7
Hyper	77	330	76	2	11
Hyper	78	300	75	nm	9

Table 1 Generally hypereutectic iron (nm – not measured)

In table 2 there is a completely different chemistry practice with a slightly higher inoculation practice. Late graphite comes out during about 93% of the solidification, but it is not enough to offset the lower carbon level and higher inoculation practice. This foundry would do well to decrease their inoculation down to the 300 levels if possible. If chill problems prevent this, then they might consider raising the C.E. to produce eutectic mode solidification.

Mode	Nodularity	Nod Count	Late Graphite	Shrink	Undercooling
Hypoeutectic	84	470	93	Nm	1
Hypoeutectic	88	470	87	19	1
Hypoeutectic	89	470	92	18	1
Hypoeutectic	87	450	96	17	0
Hypoeutectic	91	470	95	22	0
Hypoeutectic	90	370	92	9	1
Hypoeutectic	94	320	95	1	0
Hypoeutectic	86	370	92	9	1
Hypoeutectic	94	320	91	2	0

Table 2 Generally hypoeutectic iron (nm – not measured)

Discussion

Shrinkage has many causes. The question is: Is shrinkage an intermittent problem or a consistent problem? Consistent problems are problems that suggest a redesign of the gating and risering system, additions of chills, and even a redesign of the casting or change in the carbon equivalent of the iron. An intermittent problem is generally where the foundryman is at a loss for a solution. While tramp elements that cause significant alloy segregation in the grain boundaries⁸ can cause small micro-shrinkage by lowering the grain boundary freezing temperature, this discussion is directed more toward graphite control to offset normal macro-shrinkage.

There are four solidification modes that can occur in ductile iron: hypoeutectic, hypereutectic, eutectic, and a combination of hyper-hypoeutectic. These classifications are applied to the shape of the thermal analysis curve, not the chemistry. These curves may differ from what can be expected from chemistry because of the speed of cooling and the suppression of graphite formation due to magnesium. Faster cooling will shift the mode from hypereutectic toward eutectic, and from eutectic toward hypoeutectic as carbon has less time to precipitate.

In the hypoeutectic mode there is an austenitic liquidus arrest, followed by a eutectic arrest. In the hypereutectic mode there is a graphitic liquidus arrest followed then by a eutectic arrest. In the eutectic mode there is only a eutectic arrest. In the hyper-hypoeutectic mode there is first a graphitic liquidus arrest followed by an austenitic liquidus arrest, and then finally, the eutectic arrest.

Hypereutectic Mode

In a hypereutectic mode iron, graphite nodules first form in the liquid. This is a moderately low energy reaction that may go on for some time. The heat generated from the graphite slows the cooling rate, and therefore prolongs the length of the arrest. Since no solid metal is precipitated during this arrest, the

walls of the casting are thin to non-existent depending on the temperature gradient.

During this cooling time, the expansion due to the graphite may simply push iron back into the riser, or, if it is a riserless casting or the gating is frozen off, will cause some mold wall movement, if the wall is still thin or the liquid is still a large portion of the casting.

The formation of graphite nodules in the liquid reduces the remaining carbon in the iron down to the eutectic level. Assuming a 3.9 carbon and a 2.4 silicon iron (C.E. of 4.7), this will lead to a carbon level remaining in the liquid of 3.53% with the balance of 0.37% going to expansion in the liquid riser or mold wall movement.

$$4.33 \text{ C.E.} - (2.4 \text{ Si} / 3) = 3.53 \text{ C}$$

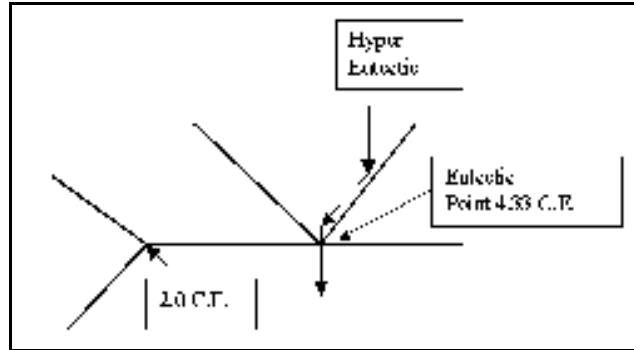


Figure 4. Hypereutectic liquid iron is depleted of carbon down to the eutectic point by formation of graphite

Once the graphite liquidus is finished, the eutectic forms and the remaining carbon down to the capability of the austenite to hold carbon (2% C.E.) is rejected from the austenite in the form of graphite. Again assuming a 3.9 carbon and a 2.4 silicon iron, this will lead to the formation of about 2.7% graphite in the iron at eutectic.

$$2.0 \text{ C.E.} - (2.4 \text{ Si} / 3) = 1.2 \% \text{ C in austenite}$$

$$3.9 \text{ C} - 0.37 \text{ graphite} - 1.2 \text{ C in austenite} = 2.33\% \text{ graphite formed at eutectic temperature}$$

$$3.9 \text{ C} - 0.37 \text{ graphite in liquid} - 0.78 \text{ retained carbon} = 2.75 \text{ graphite for expansion.}$$

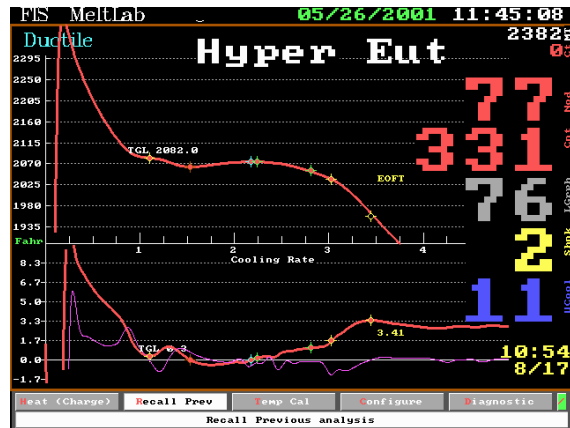


Figure 5. Note the large area of the graphitic arrest in the Cooling Rate graphic. This represents a considerable amount of graphite coming out. The energy production of the graphitic liquidus is not as great as an austenite liquidus. This iron would be subject to macro-shrink, but the micro-shrink is ok. The graphite shape is also poor with several clusters of fast growing graphite present.

The remainder of the carbon can transform into graphite as the iron cools further. The amount of retained carbon in the unheat-treated room temperature iron is about 20%¹ plus whatever carbon is retained in pearlite or carbides. If we assume no pearlite, then the total expansion of the graphite that benefits fighting shrinkage would be 2.75%, and the wasted graphite expansion would be 0.36% or 13% of the total expansion of graphite.

Hypoeutectic Mode

In a hypoeutectic mode, an austenite liquidus forms, and dendrites grow into the liquid, increasing the carbon content of the remaining liquid. This iron will develop a stronger casting wall to resist mold wall movement, but will have less graphite formed to offset macro-shrinkage. For an iron with 3.4 carbon and 2.1 Silicon (C.E. of 4.1), a little less than 10% of the casting will be solid before the eutectic is reached.

$$2x + (1-x) \cdot 4.33 = 4.1 \text{ C.E. (lever rule)}$$

$$x = 9.87\%$$

At the eutectic, the graphite formed would be 2.1%

$$2.0 \text{ C.E.} - (2.1 \text{ Si} / 3) = 1.3 \% \text{ C in austenite}$$

$$3.4 \text{ C} - 1.3 \text{ C in austenite} = 2.1\% \text{ graphite formed at eutectic temperature}$$

$$3.4 \text{ C} - 0.68 \text{ retained carbon} = 2.72 \text{ graphite for expansion.}$$

Applying similar logic to the previous example, we would gain a total of 2.72% graphite to fight expansion. This is not much different than the hypereutectic mode result.

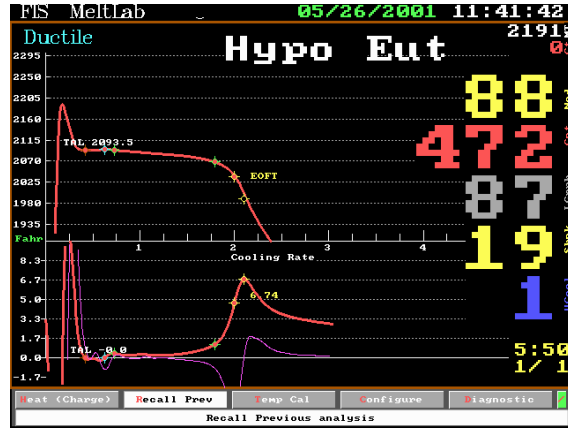


Figure 6. Hypoeutectic mode solidification: austenite liquidus and eutectic

Eutectic Mode

In the eutectic mode, there is no liquidus arrest. Due to the presence of magnesium, a single arrest (eutectic) mode can occur between 4.3 C.E. and as high as a 4.6 C.E. Assuming 2.4 silicon, this iron could contain from a 3.5 to a 3.8 carbon. At the eutectic, this would produce a range from 2.3 to 2.6% graphite: a variation of 13%.

- 2.0 C.E. – (2.4 Si / 3) = 1.2 % carbon in austenite
- 3.5 C – 1.2 C in austenite = 2.30% graphite formed at eutectic temperature
- 3.8 C – 1.2 C in austenite = 2.60% graphite formed at eutectic temperature
- 3.5 C – 0.70 retained carbon = 2.80% graphite for expansion.
- 3.8 C – 0.76 retained carbon = 3.04% graphite for expansion.

Applying similar logic to the previous examples, we would gain a total of between 2.80% and 3.04% graphite to fight expansion. There is no liquid expansion problem, and the 3.8% carbon example has 13% more beneficial graphite than the slightly higher 3.9% carbon hypereutectic iron.

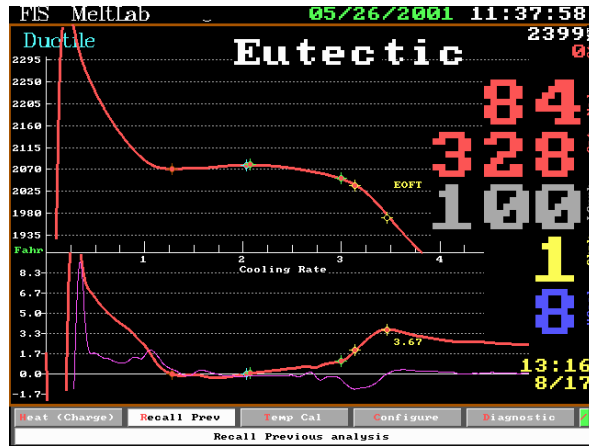


Figure 7. Single arrest eutectic mode solidification

Hyper-Hypoeutectic Mode

This mode occurs more often than suspected. A large graphitic liquidus starts a reaction that removes so much carbon from the liquid, (possibly through flotation) that the remaining liquid turns hypoeutectic, and an austenite liquidus follows. This material has the worst aspects of a hypereutectic iron (mold wall movement, no appreciable wall thickness, low graphite contribution to fight shrink) and has all the bad aspects of a hypoeutectic iron (even lower graphite contribution to fight shrink).

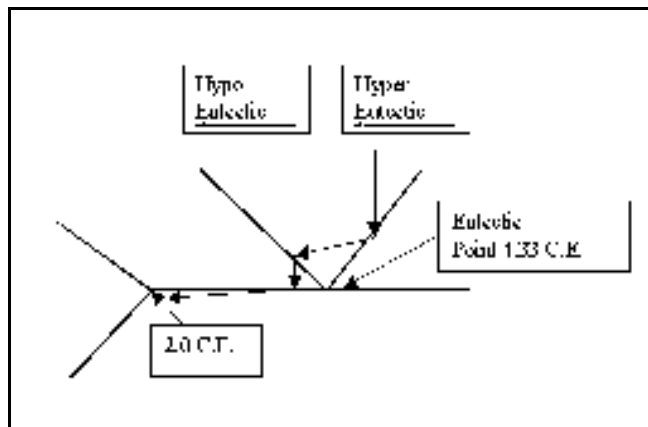


Figure 8. Expanded region of eutectic zone due to magnesium suppression of graphite formation.

Assuming a 3.9 carbon and a 2.4 silicon iron (C.E. of 4.7), and that the iron falls to a 4.25 C.E. this will lead to a carbon level remaining in the liquid of 3.45% with the balance of 0.45% going to expansion in the liquid riser or mold wall movement.

$$4.25 \text{ C.E.} - (2.4 \text{ Si} / 3) = 3.45 \text{ C}$$

The eutectic forms, and the remaining carbon down to the capability of the austenite to hold carbon (2% C.E.) is rejected from the austenite in the form of graphite. Again assuming a 3.9 carbon and a 2.4 silicon iron, this will lead to the formation of about 2.6% graphite in the iron at eutectic.

2.0 C.E. – (2.4 Si / 3) = 1.2 % carbon in austenite

3.9 C – 0.45 graphite in liquid – 1.2 C in austenite = 2.25% graphite formed at eutectic temperature

3.9 C – 0.45 graphite in liquid – 0.78 retained carbon = 2.67 graphite for expansion.

The remainder of the carbon can transform into graphite as the iron cools further. The amount of retained carbon in the unheat-treated room temperature iron is about 20%¹ plus whatever carbon is retained in pearlite or carbides. If we assume no pearlite, then the total expansion of the graphite that benefits fighting shrinkage will be 2.67%, and the wasted graphite expansion will be 0.45% or 17% of the total expansion of graphite.

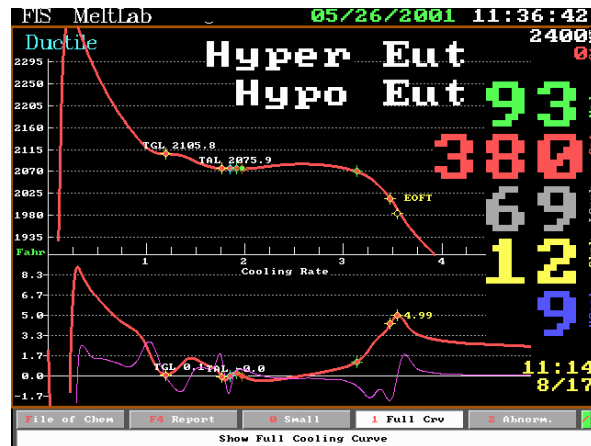


Figure 9. The two liquidus arrests are followed by the eutectic arrest. The first liquidus arrest is large but not energetic (graphitic). The second liquidus arrest is small but very energetic (austenite).

Conclusion

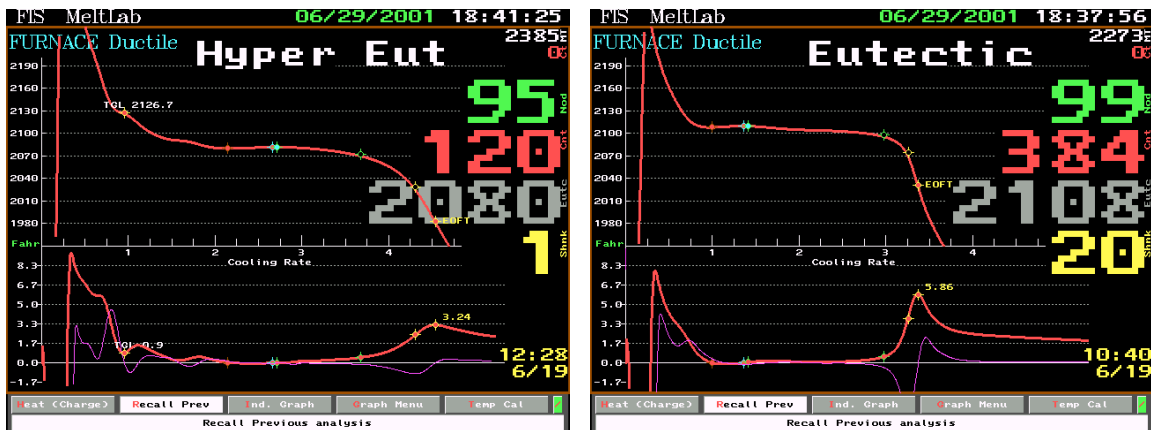
Macro-shrinkage is the result of the interaction of several complex influences in the iron. If the shrinkage is constantly present from day to day, then the gating and risering vs. the iron chemistry needs to be revised. But if the problem comes and goes, and the chemistry seems to be consistent during these episodes of shrinkage, then the problem is most likely in the control and timing of the graphitizing process.

Magnesium opens up the C.E. range of a eutectic iron by inhibiting the formation of a graphite liquidus. This opens up the possibility to have more carbon in the iron to offset shrinkage so long as no graphitic liquidus occurs. This phenomena needs to be studied more in terms of effective magnesium vs. carbon level vs. inoculation.

Small-localized carbon flotation may be far more common than previously thought, and can result in slow cooling sections anytime that the graphitic liquidus occurs in that section size. This can account for 15 to 20% less graphite being available to counteract the macro-shrinkage. This can also occur in iron when the carbon equivalent is on the high side of safe. Inoculation may also influence the appearance of the graphitic liquidus.

The eutectic mode of freezing with irons that are above the eutectic in chemistry will give the most “late graphite” to counteract macro-shrinkage. There is as much as a 13% gain in late graphite possible with this mode of solidification. Likewise, irons of the same C.E. level that are lower in silicon will have more graphite to counteract shrinkage.

Thermal analysis provides a unique picture of how all these factors combine together to produce different modes of freezing. It can identify irons susceptible to carbon flotation, as well as when the iron will have a graphitic liquidus.



This shows the before and after of in-stream inoculation. Grain boundary shrink (tension) rises from an index of 1 to 20 with the production of a eutectic arrest, and shows a lack of macro-shrinkage which would relieve the grain boundary tension.

References

1. T. Skaland and O. Grong: "Nodule Distribution in Ductile Cast Iron," *AFS Transactions 91-56*, p 153-157 (1991).
2. Torbjorn Skaland: *A Model for the Graphite Formation in Ductile Cast Iron*, University of Thronheim, Sweden. (1992)
3. R.W. Heine: "Nodule Count: The Benchmark of Ductile Iron Solidification," *AFS Transactions 93-84*, p 879 (1993)
4. R.W. Heine: "Carbon, Silicon, Carbon Equivalent, Solidification, and Thermal Analysis Relationships in Gray and Ductile Cast Irons," *AFS Transactions 72-82*, p 462 (1972)
5. D.M Stefanescu, H.Q. Qiu and C.H. Chen: "Effects of selected metal and mold variables on the dispersed shrinkage in spheroidal graphitic cast iron," *AFS Transactions 95-057*, p 189 (1995)
6. T.N. Blackman: "Graphite Flotation in Ductile Iron Castings," *AFS Special Report* (1988)
7. A.G. Fuller, T.N. Blackman: "Effects of Composition and Foundry Process Variables on Graphite Flotation in Hypereutectic Ductile Irons," *AFS Special Report* (1988)
8. R. Boeri, F. Weinberg: "Microsegregation in Ductile Iron," *AFS Transactions 89-106*, p 179 (1989)
9. Richard Fruehan: "Gases in Metals," *ASM Handbook volume 15 Castings*, p 82 (1992)
10. D.A. Sparkman, C.A. Bhaskaran: "Chill Measurement by Thermal Analysis," *AFS Transactions 96-127*, p 969 (1996)
11. David Sparkman: "Using Thermal Analysis Practically in Iron Casting," *Modern Castings November 1992*, p 35