



Solidification mode and feeding ductile castings

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To fully understand how castings solidify, it is important to understand how the different components of iron form in the casting. These components are: austenite free of graphite in the form of dendrites, graphite in the liquid melt that is free of austenite and eutectic material where graphite forms in austenite shells. The metal solidifies based on chemistry, magnesium treatment, which causes a form of graphite modification, and inoculation levels can be seen through a thermal analysis sample of the metal. The chemistry alone is insufficient to predict the solidification mode, and the foundries that depend solely on chemistry are often disappointed with the casting results.

There are four known modes of solidification for ductile iron: hypo-eutectic, eutectic, hyper-eutectic, and a combination of hypo and hyper eutectic modes. The following graphs are from a more complete paper entitled “*Converting thermal analysis information into microstructure information*”¹ as well as an earlier paper “*Offsetting Shrinkage in Ductile Iron - What Thermal Analysis Shows*”². All the samples and all discussions of thermal analysis in this paper assume the use of a “plain cup” or a cup without tellurium in it. These samples froze much like a casting of the thickness of the sample cup.

Here is a set of graphs and diagrams of the four modes. On the left is an actual analysis curve of a treated ductile iron sample and on the right is a diagram showing a partial iron-carbon phase diagram and how the liquid chemistry changes during solidification. In the first example, the carbon equivalent starts out above and to the right of the eutectic. Graphite precipitates out and the remaining liquid’s chemistry, now lower in carbon, shifts to the right until the eutectic point is reached and the remaining liquid solidify.



Fig 1. A final hyper-eutectic ductile iron curve showing a tiny near invisible graphitic liquidus arrest.

If only the temperature curve was observed, the small graphite arrest would have been missed. This sample will show some small amount of bimodal graphite distribution due to the very small size of the graphite arrest. There is no sign of shrinkage in the TA curve, and the eutectic region of the curve is very quiet, which indicates extremely good nodularity.



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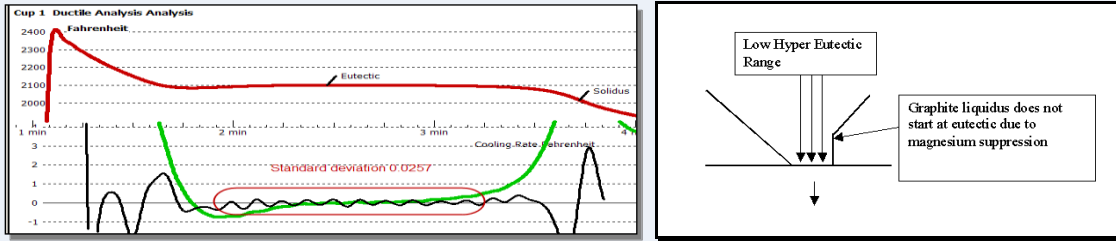


Fig 2. A final eutectic ductile iron curve showing only a single arrest.

Here, there is no apparent graphite arrest, just a single eutectic arrest, though the iron is not a true eutectic iron, in that the C.E. is higher than 4.3, the freezing mode is. The key is that the magnesium added to ductile iron suppresses the formation of graphite and creates a range of C.E.s where eutectic mode freezing can occur. This is extremely important because eutectic mode freezing does not block the gates with dendrites, and better feeding occurs. On the negative side, casting walls are slower to thicken and gain strength. This type of iron is normally not used in large castings.

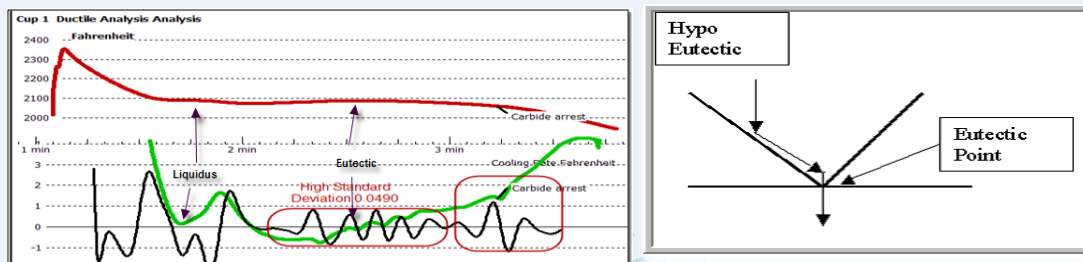


Fig 3. This is a final hypo-eutectic ductile iron curve with an austenite liquidus and a eutectic arrest. The carbide arrest comes in conjunction with poor nodularity.

This is a hypo-eutectic sample of iron that typically will have some shrinkage in it. The C.E. starts out below eutectic, and dendrites grow from the walls of the casting into the melt until the remaining liquid is of eutectic composition. The dendrites add to the strength of the casting walls, but tend to also choke off the gates early. In this example, the magnesium and inoculation was insufficient and poor nodularity and carbides resulted. Those two problems were not caused by the freezing mode.

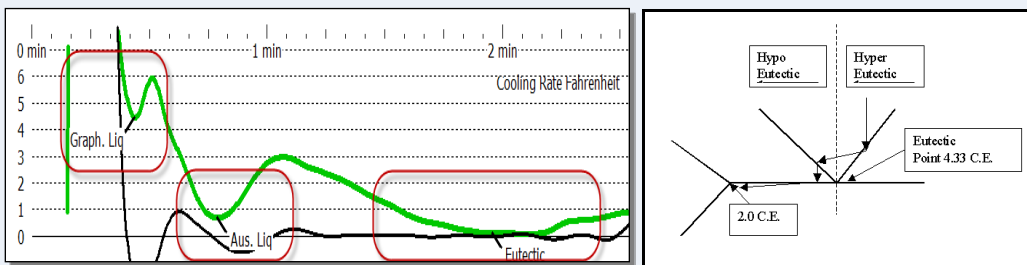


Fig 4. This is an example of Hyper-hypo-eutectic ductile iron having both a graphite liquidus and an austenite liquidus arrest common in Hyper-eutectic irons above 4.6 C.E.³. The appearance is slightly different than figures 2 and 3, due to the change in the scale needed to include the graphitic liquidus.

This final mode is not well documented in the literature, and many do not even know it exists. Professor Heine did find some triple arrest iron in his early TA investigations of high C.E. ductile iron in the late 60's and early 70's but did not identify the cause of the third arrest. The old foundrymen have also talked of "carbon flotation" where there is an area rich in graphite nodules physically located above an area poor in graphite, but rich in shrinkage.



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Perhaps this is what they were seeing. What has happened here is that graphite came out in the liquid with enough vigor to remove too much carbon and the C.E. of the remaining liquid dropped below the eutectic point. This transformed the liquid into the hypo-eutectic chemistry range, so we had an austenite liquidus as well. I am not sure how common this is, but it cannot be good for making solid castings.

Let's look at the molten iron and watch how the metal solidifies in each instance, and what that means for the gating system. The risers in ductile iron are generally large, and the gating and risering system account for half of the poured weight in a typical ductile mold. The finished casting will be composed of 9 to 11% graphite by volume, and the balance in steel. In pattern making, steel has a shrink rule of 10%. If we can indeed achieve 10% graphite in the casting, you would think we would have a solid casting. It is tough, and missing by 1% graphite can make a lot of shrinkage. (A 1% shrinkage in a 5 pound casting, is a hole the size of your thumb.)

First, the risers are designed to feed the casting cavity as long as possible. This requires that the gates be open. Hypoeutectic iron makes austenite dendrites that grow from the walls and tends to close off smaller gates early. Smaller castings are usually made with eutectic freezing mode iron because it feeds better through smaller gates and runner systems. On the other hand large castings with their massive risers and larger gates are made with hypo-eutectic iron. With the larger gates and risers, much of the large casting can become solid while the gates and the risers retain liquid and remain open. Large castings can have a problem with higher carbon content iron and long freezing times producing graphite.

Small and medium size castings are made with eutectic or slightly hyper-eutectic iron that freezes as eutectic iron. This iron can feed the casting to offset metal shrinkage down to at least the eutectic temperature, if not slightly below. The sand in the gate area is generally hotter than the walls of the rest of the casting so the gates do not freeze quite as quickly as the same section size in the casting, but they generally do freeze off before all the casting is solidified. Once the gates freeze off, it is then up to graphite growth in the casting to offset the shrinkage due to cooling. It is important that the gates freeze off before the risers do so that the casting does not feed the riser. But the problem with solid risers is not always due to the design of the gating system, as we will see later.

Graphite expansion is the key to making solid castings, especially in the medium-to-small size. In liquid iron, the carbon atom can squeeze in between iron atoms and not add to the volume of the metal. But as the metal cools, the space between iron atoms changes in two steps. At the eutectic temperature the metal assumes a face centered cubic (FCC) structure which can hold only about 2% carbon. The rest of the carbon is squeezed out and becomes graphite. As the temperature falls, the graphite continues to grow and remove carbon from the metal. Finally, as the metal reaches the eutectoid temperature of about 1440 to 1400 degrees F, the structure changes into a body centered cubic (BCC), and the last of the carbon remaining is transformed into various forms of carbides that include pearlite, martensite, or bainite. (Note: large carbides such as in figure 3 can and do form toward the end of the eutectic.) The growth of graphite then is an ongoing process that continues from the eutectic down to the eutectoid temperature and balances the continued shrinkage of the hot casting.

Pearlitic castings use alloying to stretch the matrix of the metal and make room for more than the normal amount of carbon to be retained in the spaces between the larger atoms of iron. Every 0.1% carbon so retained will produce 12.5% pearlite, but decrease the volume of the casting by 0.026%. So a fully pearlitic casting would be giving up 0.2% of volume, or about 0.5 cc shrinkage in a 2 kg casting, due to the carbon lost to make the pearlite.



Should the graphite growth begin while the gates are still open, there is a risk that the graphite volume growth will push iron back out of the gate and into the riser and runner system. This is especially the case when there is a strong graphite liquidus. Several producers make special inoculants that are good at suppressing early graphite while promoting later graphite. These inoculants in conjunction with the right C.E. can help make your castings more reliable.

Does a higher C.E. improve casting soundness? Let's assume a eutectic iron of 3.5% carbon and 2.4% silicon for a 4.3% C.E.. The Silicon is moderately high and should lead to good chill suppression. Should we raise the C.E. to 4.5% by raising the carbon to 3.7% then we will get 0.2% more graphite or an increase in volume of 0.5% of the total volume of the casting. This is good so long as we don't produce a graphitic liquidus and start expanding too early while the gate is still open.

$$((0.2\%C/3.5\%C)*\sim 10\%volume) = 0.57\% \text{ increase in casting volume at 3.7\% Carbon}$$

Shrinkage in ductile iron comes in many forms. Some is diffuse, some large and concentrated, and some are surface suck-in's. Besides looking at the TA cooling curve, you can look at the actual sample cup. The center top of the cup is usually the place to find suck-in (hypo-eutectic). Sometimes the top of the cup bulges out (eutectic or hyper eutectic). And sometimes the cup has a small ball of iron that is pushed out of the surface (late graphite expansion).

In conclusion, making good, sound castings is a science affected by the chemistry, the degree and kind of inoculation, the gating system, and the freezing mode. My boss once asked me if we should raise the carbon content of the ductile iron 10 points to reduce shrinkage. I suggested 5 points, knowing that 10 points would kick us into graphitic liquidus and cause us to have to rethink our entire gating system. We went with 5 points. The silicon level might also be considered. Lowering the silicon level will allow more carbon at the same C.E. level, but the silicon does play a big role in chill suppression and graphite formation. Silicon also plays a role in low temperature ductile iron fracture strength. So be careful changing it.

P.S. The chemistry of the iron changes during pouring. The smoke rising from the iron is mostly carbon, so I always figure a loss of 3 to 5 points of carbon each time the iron is transferred by pouring. Don't judge C.E. based on base iron or the transfer ladle. Look at the final iron going into the mold.

¹ David Sparkman "Converting thermal analysis information into microstructure information"
www.meltlab.com 2010.

² David Sparkman "Offsetting Shrinkage in Ductile Iron - What Thermal Analysis Shows" first published 2001, in the Ductile Iron Society Newsletter. Currently available at www.meltlab.com

³ Cees van de Velde "The Hyper-eutectic Region of the Iron-Carbon Diagram" <http://members.lycos.nl/cvdy/> 2004