



Finding Shrinkage in Ductile Iron Castings by TA

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The problem of shrinkage has haunted pattern engineers for ages. Is it the pattern or is it the iron, was the argument I had many a time when I was a Quality Control/Plant Metallurgist with Dana. Looking in retrospect, it was mostly the iron. The concept of timing graphite growth with the freezing off of the in-gates was not well understood at the time and we made a lot of solid non-feeding risers. So let's go over the concepts and see how thermal analysis can help.

First, let's look at the problem. Ductile iron consists of a matrix of steel surrounding graphite. Steel has a shrinkage rule of 10%. That means that pattern engineers design a steel casting pattern to be 10% larger than what the finished product will be. Second, carbon, dissolved in the liquid iron, does not add to the volume of the iron: the carbon hides in the interstitial space between Iron atoms. On the other hand, Graphite (a form of carbon) occupies 9 to 11% of the volume of the casting. So, if we could make the graphite take the place of the shrinkage, we could make a solid casting with a shrinkage rule of 0%. As we all know, it is not so easy.

Phase One – Liquid cooling, in-gates still open

First, let's look at the liquid cooling phase of the casting: the casting cavity is full of iron, and it needs to lose another 100 degrees before solidification starts. At this point, the liquid casting is shrinking: the volume of the liquid goes down as the temperature goes down. For this period, we depend on the gating system and the riser to make up the loss of volume in the casting. Soon, the runners freeze off and it is just the riser, in-gates and casting that is still liquid. Now the freezing mode becomes important.

In a hypo-eutectic freezing iron, dendrites form at the low temperature spots and start building strength and wall thickness. The casting needs as much strength as possible and the riser needs to have a weak point where the wall can be sucked in to form shrinkage. Some put a v-shaped notch in the riser to help this occur. A hot spot in the casting will transfer the suck-in and hence shrinkage to the casting. In addition, the dendrites will slow the feeding process, and if the gate is too small, choke off the feeding prematurely.

In a eutectic freezing iron there are no dendrites and the gates stay open longer. This is generally the preferred freezing mode for smaller castings. Larger castings have larger gates to make dendrites less of a problem, and they have much longer cooling times, which increase the chance of carbon flotation. But eutectic freezing irons are slower to develop wall thickness and the resulting strength, and are therefore more susceptible to mold wall movement and suck-in.



In hyper-eutectic freezing iron, graphite forms in the liquid metal. Since the gates are still open, the benefits of this expansion in volume are lost: the volume gained in the casting is pushed back into the riser/runner system.

Phase Two – the in-gates freeze off as the casting solidifies

Once the in-gates freeze, pressure in the casting can begin to rise from graphite growth. One of two things can happen: either the increase in graphite offsets the shrinkage (negative pressure), or, if the graphite comes too soon, and the wall strength is too low, the casting swells and pushes back the mold walls a fraction (mold wall movement). The latter, of course, is disastrous to casting integrity.

So the timing and amount of graphite growth along with the mode of freezing is key to producing sound castings. The timing of the graphite seems to be controllable by different inoculants. Several inoculant producers have done considerable research into producing products that promote late graphite growth.

The Iron-Carbon phase diagram suggests that only 2 percentage points of carbon out of a typical 3.8% or slightly over half of the graphite is formed during the eutectic freezing. I suspect that the actual number is larger as the phase diagram is for steady state, and castings certainly are not steady-state creatures. Nevertheless, graphite growth continues from the eutectic temperature down to the eutectoid temperature at which point most remaining carbon transforms into pearlite or martensite. Pearlitic type irons contain alloys that retard the movement of carbon to the graphite form and so, because less graphite is formed, the shrinkage potential of these irons is greater.

During the time that the casting is still soft and plastic, it can be thought of as being under a negative pressure or “wanting” to shrink to relieve this vacuum. The shrinkage forces are either released by the formation of actual shrinkage or by suck-in, or they manifest themselves in the final freezing at the grain boundaries as stress. If the result is stress in the grain boundaries, then this stress will be partly to completely relieved by the continued growth of the graphite and the casting will be solid. Of course, in the real world there can be in between solutions such as stressed grain boundaries and shrinkage, but as the shrinkage goes up or suck-in occurs, the stress in the casting is reduced.

Thermal Analysis understanding of shrinkage

There are three bits of information that thermal analysis can give the foundry on shrinkage: the freezing mode, the amount of late graphite vs. early graphite formation and finally, the total shrinkage stress remaining in the casting.

Freezing Mode

There are two good modes of freezing: hypo-eutectic mode for larger castings, and eutectic mode for smaller castings. I use the term “mode” because the mode is not completely determined by carbon equivalent. Magnesium suppresses the formation of graphite, so that you can get a eutectic mode



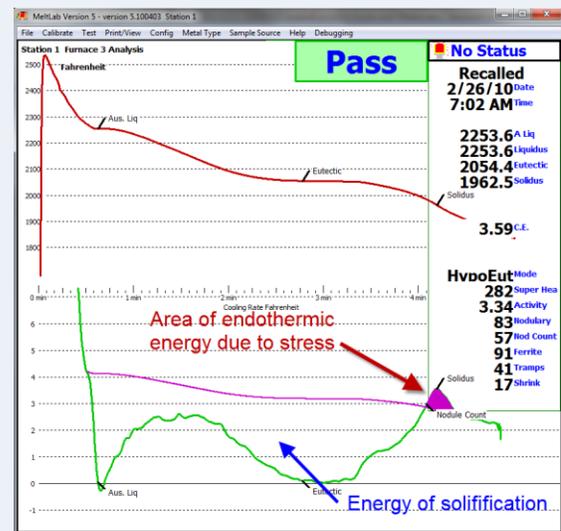
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between 4.33 and about 4.55 (maybe 4.60) C.E. My definition is simply to look at the arrests. If there is an austenite liquidus, then it is hypo-eutectic. If there is no liquidus, then it is eutectic. Please note that MeltLab will uncover even a small liquidus often missed by other instruments.

Then there are two not-so-good freezing modes: hyper-eutectic and hyper-hypo-eutectic (carbon flotation). In the first mode, graphite forms in the liquid, and its volume increase is lost into the riser/runner system as mentioned before. In the second mode, the non-steady-state nature of the iron allows the rapid graphite growth in the liquid to remove so much carbon that the remaining liquid falls below 3.33 C.E. and an austenitic liquidus forms. In both cases the casting will end up with shrinkage of about 1% of the casting volume. That 1% translates into a hole the size of your thumb for a 5 pound casting and of course, it is right where your customer needs it the least (Murphy’s Law, corollary 13). I first noted the hyper-hypo-eutectic mode from some of Professor Heine’s early work on Ductile Iron TA, where he described a hyper-eutectic iron with three arrests, but did not clarify what those arrests were (Graphitic Liquidus, Austenitic Liquidus, Eutectic).

Graphite distribution

This work was originally pioneered by NovaCast in their ATAS system. By extensive correlation they found that the length of time during the eutectic freezing could be split into two areas: the part before the eutectic point and the time after the eutectic point. To clarify, eutectic freezing occurs over a range of time and temperature, but in TA, a single temperature is chosen out of that period to represent the eutectic temperature. That point is defined as the “strongest” (read “highest temperature”) point in the eutectic reaction. In MeltLab, that is just the zero crossing of the first derivative if there is one, or the zero crossing of the second derivative if there isn’t one. If we ratio the second segment (S2 in ATAS) to the first one (S1 in ATAS) we come up with an S2/S1 ratio with the larger the number, the better. In a similar manner you could take $S2/(S1+S2)$ and come up with a percent of time for the late graphite growth vs. overall graphite growth. This number is mostly controlled by the effectiveness of the inoculation and the inoculant. MeltLab reports this percentage as well as the S2/S1 ratio, though I think the percentage is an easier number to understand.



Grain boundary Stress

The final measure of shrinkage and one of the best methods (IMHO) is the residual stress in the grain boundaries. While sometimes we do get an actual shrinkage arrest showing up on the thermal analysis, often the cup sample simply has a suck-in and so no shrinkage arrest. NovaCast also uncovered a



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correlation between the value of the grain boundary stress and shrinkage, but they simply took the 1st derivative value at the point the grain boundaries froze (solidus point). I thought it would be better to actually measure the energies involved. NovaCast was measuring the height of the triangle as an estimate of the area of the triangle. While this was good, the values change with the amount of iron in the sample cup. MeltLab has the added ability to measure the area of the triangle and then ratio it against the overall energy of solidification, thereby removing the variation from sample size up to a point¹. This works because we expect a certain amount of stress, if indeed we have strong casting walls to fight suck-in and no actual shrinkage has occurred to relieve this stress. With 40% of the carbon still migrating toward the graphite nodules, there should still be stress in the casting. If not, then something bad (shrinkage or suck-in) relieved the stress.

Summary

Decide what C.E. you need for your casting. If it is hypo-eutectic, then don't cross the line and accidentally make eutectic iron for those castings. With the weak casting walls of eutectic iron, you face mold wall movement and/or suck-in. The gating systems need to be different – smaller gates for eutectic, larger for hypo-eutectic. If you need eutectic iron for your castings, you can help by making the C.E. to the high side to provide more carbon for late graphite growth. But if you step over the line (around 4.55 to 4.60) and get graphite growth in the liquid (hyper-eutectic mode), you lose all the benefit and potentially end up with even more shrinkage. So the freezing mode of your iron is very important.

Determine the best kind and the best amount of inoculant based on increasing late graphite and nodule count. Thick wall castings don't need high nodule count: thin wall castings need high nodule count to avoid chill. Worst case, you may need to put a thermal couple in a casting/riser to find the optimum levels based on casting thickness. Watch the percent late graphite to make sure your process and your material are performing correctly and consistently.

Finally, use the "stress test" as a final test to see that everything is in balance. We have lots of variables in our foundries and, though we don't always know the cause of changes, this is a useful final "goodness" test of how well everything is performing together. Not all castings have to be totally shrinkage free. A little finely dispersed shrinkage in a heavy section can often be tolerated. The castings just need to not have large shrinkage right where the customer needs solid metal.

MeltLab is a tool for understanding solidification problems. Coupled with a smart human mind, the life of a melter, a metallurgist or a pattern engineer can be a little easier.

¹ A funny story: I went into one foundry having problems with their MeltLab. They poured a sample and showed me that the system didn't work. I walked over to the cup and noticed that the thermal couple was sticking up out of a cup that was only 1/3 filled with iron. Yep, it didn't work. I got them a ceramic spoon to replace their iron spoon: more volume, less frozen iron on the spoon. Cup needs to be full or nearly full, or at least cover the thermal couple. Procedures do count.