Balancing graphite growth and shrinkage in ductile iron

by David Sparkman June 2nd 2010 all rights reserved

Last month, I discussed the miracle of ductile iron: that the graphite volume offsets the shrinkage of the steel matrix in ductile iron – for the most part. I tried to find out how the density of the iron changes from molten to solid to room temperature. Unfortunately there is no “good” information that can be modeled. From science, I would expect a significant loss in volume as the iron changes from liquid to solid, but can find no information other then guesses using the 10% rule. Wikipedia lists the density of molten iron (pure) at 7.874 grams/cm^3 at just above the freezing point and as 6.98 grams/cm^3 at room temperature. What is missing is the volume change going from liquid to solid at the freezing point.

So let’s start over. The proposition is that the endothermic arrest seen in ductile iron thermal analysis just before and just after the solidus point (grain boundary freezing) is due to the contraction of the metal exceeding the expansion of the graphite during that time.

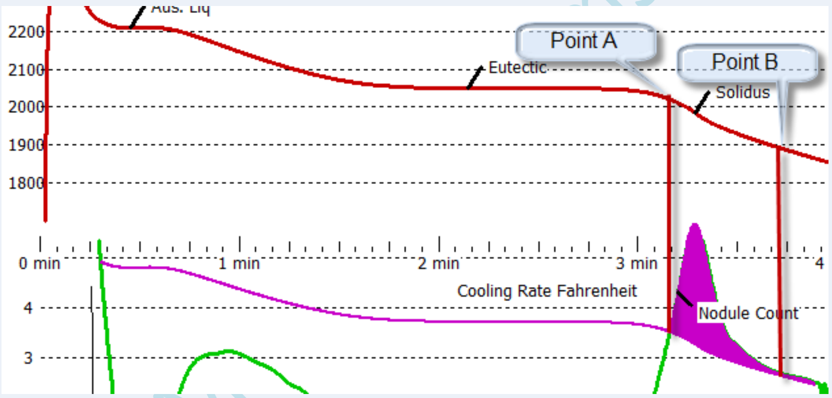
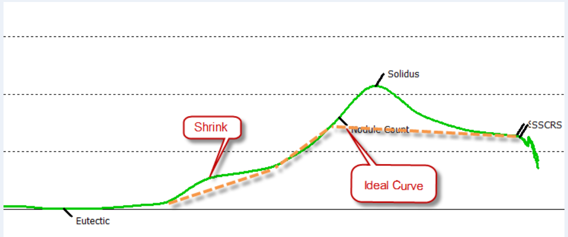


Fig. 1 highly stressed, but non-shrinking iron

At point A the shrinkage of the matrix exceeds the production of graphite volume. At point B, the stress has disappeared due to what I assume is the graphite growth. I looked at several curves with low shrinkage for the temperatures where the stress begins and ends. Please remember that the “end” we are looking at is the end of the generation of MORE stress. The original stress has not yet been compensated for. At this point, either the iron has completed solidification, a phase change from liquid to solid, and/or the graphite growth is catching up with the changing volume. The shrinkage arrests that we do see seem to happen before the stress arrest, and of course, remove the stress by providing a relief valve.

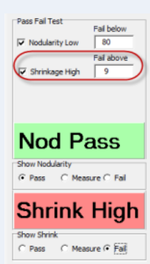


Here is an example of a shrinking iron with a shrink arrest occurring at 2100˚ F and ending at 2080˚ F. During these this temperature range there is still considerable liquid present in the casting (about 10%). The ideal curve is presented as one with no shrinkage and no stress: i.e. a volume change of zero. It is important to understand that the stress arrest only begins when the casting begins to take on strength and the amount of liquid becomes almost zero. The actual loss of volume is beginning earlier during the eutectic arrest, and so the visible shrinkage arrest occurs before the casting has strength to resist it and before stress can build up.

Understanding this, I went back and asked the program to identify point A. Point B is already identified as the point that steady state cooling sets in, what I call the SSCRS or steady state cooling rate of a solid and is the lower anchor point of the zero curve. Taking a relatively small sample of tests from a single foundry, I came up with 2026˚ F as the average starting point of the stress arrest, and 1980˚ F as the average ending point of the stress arrest. So it is only a short period of about 46˚ F that the casting is highly stressed. Remember the eutectic is occurring at about 2100˚ F.

Based on these numbers let's look at what is happening. When the iron first changes from liquid to solid it goes through what is called a phase change (the way the atoms arrange themselves) and, typical of phase changes, it goes though a volume change as well. It appears from my data to be about a 5% volume change[1]. The graphite that forms at this time only occupies 4.3% of the casting volume leaving a deficit of about 0.7%. This deficit results in the stress arrest we see. The graphite growth will not catch up with the volume lost until about 1880˚ F and so all internal shrink has occurred before this temperature.

As the casting cools further, it will lose another 5% volume due to temperature, but will continue to gain graphite volume and will gain strength to resist further shrink formation. As far as I know, no one else has presented numbers to describe this phenomenon so there is no source to quote.



Summary

So how does this help the foundry make a better casting? As an engineer, I am always looking for what works, and this is a good test of what works. If you monitor your iron with such a test, you will be able to detect times when you are moving in the direction of unacceptable shrink due to your iron. The combination of multiple variables can make that forecast complex, but the actual test removes doubt and reduces scrap. It is a simple

[1] Since the stress arrest ends when the graphite approaches 5%, I concluded that the initial volume change was 5% while the calculated graphite volume was only 4.3% at the temperature the stress arrest started at.

and quick test and with a pass/fail system, you can set it up for the pouring people to be able to understand the test. The stress energy is compared to the ideal stress energy, and if the difference (ideal – measured) is larger than a given value, the iron is reported as “Shrink High”.

Finally, I would like to revisit another problem: mold wall movement. This concept says a soft mold may allow the casting cavity to enlarge at a point during solidification where the risers can no longer provide feed metal to the casting. The enlarged volume then has no choice but to produce shrinkage. To fight this, larger risers and gates that are slower to freeze off are recommended as well as harder molds. The definitive test for mold wall movement is a casting that is slightly larger dimensionally than it should be - which in my mind is a tough call.

If a casting with shrink is dimensionally larger than a casting without shrink, do we assume mold wall movement? I suggest not. Consider the following scenario. A casting has an internal shrink due to chemistry of 0.5% of volume[2]. This shrink is all internal and there is no suck-in. As the casting continues to cool, the graphite continues to develop, and the same 10%-12% of volume of graphite forms just as it does in a companion casting with no shrinkage. The hydrostatic pressure from this graphite is tremendous and cannot be resisted. Some of the shrink will be reduced in volume, but the remainder of the volume must go somewhere, and it goes to increase the volume of the casting that has shrink, in other words, the casting with shrink will have greater volume than the casting that didn’t shrink, by the volume of remaining shrinkage.

So a casting with shrink that is dimensionally larger did not necessarily suffer from mold wall movement. The shrink itself would have caused the increase in casting volume. Your comments are welcomed.

Another issue is gas formation in some irons that may enhance the shrinkage. Gas forms smooth surfaces in the shrinkage, while true shrinkage often has tiny dendrites on the surface. Both can occur at the same time, making a larger “shrink” hole.

Next month’s “Hot Topic” will be on microscopic events in solidification using aluminum “Beta” crystals as a benchmark. We will look at the energy signal of an aluminum alloy with 0.5% iron, and then compare the background noise to the beta crystal signal and the overall energy to come up with a confidence level for micro-events.

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[2] One half percent volume in a 5 pound casting would be a hole 1.626 cm^3. Most shrink problems are larger than that.