Gray vs. Ductile Shrinkage

Grey and ductile irons have very different solidification characteristics with gray iron having minimum shrinkage issues and ductile iron constantly having shrinkage issues. This month we will examine what makes the difference and what you can do to about it.

Gray Iron typically runs 3.2 to 3.4 percent carbon while ductile is more typically 3.6 to 3.8 percent carbon. The end results are also a little different. Gray iron typically is pearlitic while ductile can be ferritic, 40-50% pearlitic, 80% pearlitic or even 100% pearlitic. So since 100% pearlite requires 0.8% carbon, there is that much less graphite to counteract shrinkage. Let me explain.

First, from Wikipedia: Graphite density ranges from 2.09 to 2.23 and iron density is 7.874 so 1 gram of graphite has the same volume as 3.53 grams of iron for high density graphite to 3.77 grams of iron for low density graphite.

A 100 gram casting of iron will shrink 10% or 10 grams volume on cooling to room temperature. That volume loss could be replaced by 2.65 to 2.83 grams of graphite or 2.65% C to 2.83% C depending on the density of the graphite. Assuming high density graphite, 2.83% carbon as graphite + 0.8% carbon as pearlite gives us a total of 3.83% C. Low density graphite gives 2.65% carbon as graphite + 0.8% carbon as pearlite = 3.45% carbon to produce shrink free gray iron.

Assuming an average gray iron value of 3.3% carbon leaves us with a shortage of 0.15% C to 0.53% C which then equates to a volume loss of 0.57% to 1.87% actual shrinkage. This shrinkage occurs in three stages: liquid cooling, liquid to solid transformation, and solid cooling. The liquid cooling is generally made up by risers or a well-designed gating system and the solid state cooling shrinks the entire casting the same amount so there is no concentration of shrinkage to form internal porosity. It is the Liquid to solid transformation that we generally have to worry about.

One of the key points of gray iron is that the graphite forms during the liquid to solid transformation with some graphite flakes actually growing from the solid metal out into the liquid. The shrinkage can then go into four different places: smaller dimensions, actual micro-porosity, less dense graphite, and grain boundary disorder (stress). Since gray iron is hypoeutectic, strong walls quickly form so only in slow cooling areas (sharp fillets and hot spots) is there an actual chance of dimensional change or suck-in. These can usually be resolved by chills or redesign of the casting. The energy to form less dense graphite, or even disordered grain boundaries is considerably less than the energy required to form an interior surface or a shrinkage void. So the casting tries to hide its lost volume into these features first before actually forming shrinkage. Thus we generally find stubborn gray iron shrinkage only in unfed heavy sections.

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Ductile iron is different in that the graphite grows later. Whereas in Grey iron, the graphite growth is faster than the phase diagram suggests (level rule), in ductile iron, it is slower than the phase diagram suggests. Magnesium inhibits the formation of graphite, so it generally doesn't form in the liquid below 4.6 C.E. And even at the end of solidification (solidus), much of the graphite to be is still in the austenitic iron matrix. By my estimates, at solidus, only 50 to 60% of the total final graphite has formed. This causes a problem in the casting. Without the volume growth of graphite, the casting has a volume deficit that can push the casting over into actual shrinkage.

A 100 gram casting of ductile iron will shrink 10% or 10 grams volume on cooling to room temperature. That volume loss could be replaced by 2.65 to 2.83 grams of graphite or 2.65% C to 2.83% C depending on the density of the graphite. Assuming high density graphite (worst possible case), 2.83% carbon as graphite + 0.8% carbon as pearlite gives us a total of 3.83% C. A ferritic casting would only require 2.83% carbon, well below the typical 3.6 to 3.8% typical carbon levels. So this logic would lead one to think that all of our ductile castings should be solid. Well obviously there is a problem: only about 60% of that graphite is present when the casting is finally solid. The rest grows as the casting cools down to the eutectoid temperature of about 1400 F (745 C – varies with chemistry composition). That means that our useable graphite is only 2.16 to 2.28% at solidus leaving us with a deficit of about ½ % volume. A 5 pound casting could have a shrinkage hole of about ¾ inch (1.9 cm) diameter if that volume deficit were to result in shrinkage.

There are three things that can happen to that volume loss: it can be expressed as stress, suck-in or shrinkage. The idea casting will have it expressed as grain boundary stress because this stress will be eliminated by the later graphite growth. The suck-in and shrinkage voids don't get eliminated by the late graphite growth, but the casting may swell slightly. The trick then is to get the casting wall strength high enough to resist suck-in by eliminating hot spots, and then, somehow to avoid the concentration of stress in one area that would lead to the formation of an interior surface (a void). This is an area where more research could be done. Are there characteristics of iron such as gas that can nucleate shrinkage by reducing the energy need to start the formation of an interior surface?

MeltLab and ATAS both use the measurement of the stress level in the casting as a predictor of shrink. Higher stress is better, lower stress suggests that the stress has somehow been relieved though shrinkage or suck-in.

The following is a general discussion of the chemistry and gating of ductile iron and how it affects solidification.

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Smaller size ductile iron is generally made close to eutectic composition of 4.3% C.E.. This leads to a slow thickening of the walls, and the casting is slow to take on the strength necessary to resist shrinkage forces. But this also keeps the gating open as the gates are very slow to freeze off so good gating and risering can compensate and feed the casting though the first part of solidification whereas in gray and heavy section ductile, the hypoeutectic composition causes dendrites to quickly block off the gates.

There is sometimes a problem with the chemistry of smaller ductile iron where increasing carbon starts causing more problems than it solves. Many foundries have found that C.E. can be increased beyond 4.3% and give beneficial results. They typically run 4.4 to 4.6% C.E. and get the added benefit of more graphite and better fluidity for thin section. The problem happens when the higher carbon starts forming graphite in the liquid. As of right now, I do not know if there is an inverse relationship between graphite formation and magnesium content. But I have seen liquidus graphite arrests in irons exceeding 4.6% C.E. This also shows up in micros as a strong bimodal distribution of nodules. The nodules growing in the graphite show up as the larger nodules. These early nodules are growing during the time the gates are still open, so their volume change pushes iron out of the casting cavity and back into the runner/riser system producing sound risers. Then, of course, when the casting freezes off, there is insufficient graphite forming during solidification and cooling and so the shrink that should have happened in the risers is transferred into the casting.

To summarize:

- Start with a decision of what kind of iron to make the casting with: hypoeutectic for thick section iron, or hypereutectic for thin section iron. Castings in between or with both thick and thin sections will always be difficult.
- Provide gating designed for hypo-eutectic or hyper-eutectic and don’t mix the two. You need larger gates for hypo-eutectic and smaller gates for hyper-eutectic.
- Control your iron so that you don’t move across the hypo/hyper eutectic boundary at 4.3 C.E. due to normal production variation.
- Do not exceed the C.E. limit that begins to produce graphite in the liquidus at about 4.6 C.E.. It will defeat your gating system. Micros that show bimodal distribution or MeltLab that shows Hypereutectic graphite arrests can be used.

Of course some castings don’t have shrink probably because of the “out of sight out of mind principle” – the customer never complained and we never looked. Most of us are not so lucky.

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