ID 7133

ADVANCES IN DUCTILE IRON RESEARCH: NEW METALLURGICAL UNDERSTANDING AND ITS TECHNOLOGICAL SIGNIFICANCE

J. SIKORA[1] and R. BOERI[2]
Metallurgy Division – INTEMA -- National University of Mar del Plata Argentina
Av. J.B. Justo 4302 (B7608FDQ) Mar del Plata – Argentina.

SUMMARY

The present work gives an updated view about important metallurgical concepts, concerning the influence that solidification structure, microsegregation, piece size and austenite characteristics, exert on final microstructure, properties and processing control. The discussions are based on original results obtained by using special experimental techniques developed by the authors. New evidences about the solidification macrostructure, microsegregation patterns and austenite type (recrystallized and non recrystallized), allow a better understanding of the solidification and the solid state transformations taking place in conventional and thin wall ductile iron castings.

Keywords: *Ductile Iron, solidification, phase transformations, austenite*

1. INTRODUCTION

The production of Ductile Iron (DI) grows at a sustained rate. DI has replaced malleable irons and cast steels in most applications. The introduction of ADI (Austempered Ductile Iron) in the earlier 80', allowed the replacement of forged and alloyed steels. Currently, research efforts focus in the development of Thin Wall Ductile Iron (TWDI) technology, in order to introduce DI also into the light parts market.

Users and producers continue to seek new applications for DI. The key issues are to consistently reach high mechanical properties maintaining low production costs, and to cast sound low weight parts. Then, it is necessary to review and to increase the

[1] Professor, Full Professor - Head Metallurgy Division, jsikora@fi.mdp.edu.ar
[2] Professor, PhD, boeri@fi.mdp.edu.ar

knowledge base about DI, obtaining a thorough understanding on the relationships among piece shape and size, microstructure and properties. It is also important to highlight controversies about basic aspects, as for example solidification mechanisms and microsegregation patterns [1]. This work gives an updated view on this subject on the basis of recent research of the authors.

2. EXPERIMENTAL

2.1. Production of Samples and Characterization Methods

Melts used in the studies were produced by induction melting, in a pilot plant and also in commercial foundries. Regular raw materials, melting practice and inoculation methods were employed. Melts were cast in sand molds to produce different parts and samples, such us "Y"-blocks, rods and plates of a wide range of sizes, including TWDI plates of thickness down to 1.5 mm. Chemical compositions were among conventional ranges. Different heat treatment cycles were carried out by using electric furnaces.

The microstructure and microsegregation were characterized by using optical microscopy, EDX and SEM.

2.2. Special experimental techniques

Special methodologies developed by the work group were used. They include:

a) DAAS (Direct Austempering After Solidification) technique: It allows to reveal the macrostructure (solidification austenite grains) for DI melts cast in sand molds. It requires to carry out an austempering treatment directly on the solidification austenite. To do this, parts must be hot shaken out from the sand mold above the eutectoid temperature, and transferred to an isothermal bath. This procedure allows to retain part of the austenite (primary and/or eutectic), keeping the original crystal orientation, what makes solidification grains visible macroscopically after etching [1].

b) Color etching: It is used to create color patterns that follow the microsegregation maps, revealing the location of Last To Freeze (LTF) regions [2]

c) Special Jominy tests: Were carried out to identify and to compare the influence of non recrystallized austenite (present in hot shaken out samples) and recrystallized austenite (present in reheated samples) on the hardenability and the solid state transformations [3].

3. RESULTS AND DISCUSSION

3.1. Solidification structure, microsegregation and microstructure

The use of DAAS technique has proved that for all DI melts, including eutectic, hypoeutectic and hypereutectic compositions, the macrostructure is composed of large solidification grains, as shown in Figure 1. A very large number of graphite nodules, not visible in the figure due to the low magnification, are contained in every grain. For example, an equiaxed grain of the 20 mm round sample of Figure 1, has an average surface of about 1.7 mm^2 and contains more than 500 graphite spheroids. The number of nodules included into the volume of one grain was estimated to be larger than 18,000.

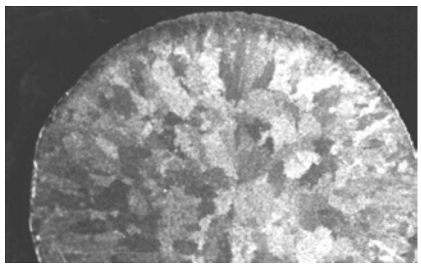

Figure 1: Macrostructure of a 20mm diameter round bar cast in a sand mould, revealed by the DAAS technique.

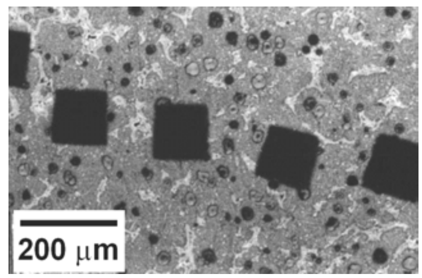

Figure 2: black and white print of a colour etched DI sample showing the location of the LTF portions as light patches.

The microscopic examination, after using color etching, allows to identify the microsegregation patterns and the LTF zones, as shown in Figure 2 for the same 20 mm diameter sample of Figure 1. Careful metallographic studies on both, grain bulk and grain boundary vicinities (revealed macroscopically and identified by micro hardness indentations) allows to establish that microsegregation is intragranular (within the grain) and not intergranular (among the grains).

The combination of DAAS and color etching techniques gives definitive evidences to establish a new solidification model for DI, disregarding the validity of other models proposed earlier in the literature [4]. Accordingly, the eutectic solidification of DI starts with the independent nucleation of austenite and graphite nodules from the melt. The austenite grows dendritically. As the solid fraction increases, the austenite dendrites collide with most graphite particles and envelop them. Further growth of the graphite is controlled by the diffusion of C from the melt to the graphite, through the austenite envelope. As each dendrite grows, it retains a large volume fraction of melt between its secondary arms. Indeed, at the time the dendrites impinge on each other defining the grain size, a large volume fraction of liquid remains inside each grain. The last melt to freeze lies between secondary dendrite arms. The dendritic arm spacing is strongly affected by cooling rate, but not by the inoculation process. For melts of similar composition and solidified at the same rate, an increase in nodule count, obtained by means of and improved inoculation practice, was not effective to diminish the heterogeneity caused by microsegregation [5].

3.2 Influence of solidification rate (Piece size)

As the wall thickness of a DI part diminishes the solidification rate increases, promoting a noticeable increase in nodule count and a decrease in austenite dendrite arms spacing.

An increase in nodule count causes an increase in the graphite-matrix interphase area (which provides heterogeneous nucleation sites), and a decrease of the diffusion distances from matrix to nodules. Both factors could lead to an increase in the rate of solid state transformations and to a refinement of the final microstructure [6].

High solidification rates also promote the formation of ledeburitic carbides. Carbides are detrimental to ductility, toughness and machinability. Nevertheless, it has been proved that large amounts of ledeburitic carbides, present in as cast unalloyed TWDI parts, can be easily dissolved during very short austenitizing cycles (less than 30 minutes holding time at 900°C) because the size of the LTF regions diminishes and are less prone to produce "microsegregation carbides" [7-8].

It was also proved that alloyed TWDI samples that solidify mottled and are later ferritized, show a greater degree of homogeneity than samples of the same dimensions that are free from carbides as cast. On the other hand, the dissolution of very small amounts of carbides present in heavier parts is much more difficult. In fact, Figure 3 shows the amount of carbides for samples of different section size of a melt alloyed specifically with elements having high carbide promotion tendency. The melt has the following composition (Wt %): C=3.58, Si=3.10, Mg=0.052, Mn=0.65, Cr=0.35, Mo=0.34. Figure 3 also shows the fraction of carbides dissolved by a heat treatment cycle, consisting in an austenitizing step at 920°C during one hour, followed by water quenching. This causes the dissolution of over 90% of the large proportion of carbides present as-cast on the thin wall samples. Meanwhile, the same heat treatment caused the dissolution of less than 30% of the small percentage of carbides precipitated at the Y-block samples. The average concentration of alloying elements in the as cast carbides for the same samples, shows noticeable differences between thin and "Y"block samples, for example: in the 2 mm thickness sample the carbides composition is Mn=1,20%, Cr=0.80%, Mo=0.40%, while in the 'Y"block (25 mm thickness) the carbides composition is: Mn=1,90%, Cr=6.20% and Mo=48.0%.

Based on these results it is possible to state that as the size of the section increases, decreasing the cooling rate, the transition from stable to metastable solidification takes place at a later stage of solidification. Carbides are formed only at the LTF regions, but from a remaining melt that is rich in carbide stabilizing elements, what cause them to be more alloyed and more stable. This points out that the presence of large amounts of carbides in as-cast TWDI is not necessarily cause of rejection of parts, particularly in those cases in which parts are to be heat treated. Furthermore, the chemical composition of the melt may include relatively large amounts of carbide forming elements, easing the control of the chemical composition of the scrap and returns used in the charge, and therefore leading to reductions in production costs.

3.3 Influence of the characteristics of the austenite

The influence that the characteristics of the austenite exert on solid state transformations of DI has been studied in detail by the authors, using conventional and special Jominy tests [7]. There is a noticeable difference in the grain size and morphology of two well distinguished types of austenite. One is the original solidification austenite, named "non recrystallyzed austenite". The other type is the "recrystallized austenite", which is produced after reheating parts above the austenitizing temperature. Non recrystallyzed austenite has large grain size and shows dendritic morphology, while recrystallyzed austenite has a noticeable smaller grain size, as highlighted in the micrograph shown in Figure 4 by a thin network of allotriomorphic ferrite, precipitated at the recrystallized austenite grain boundaries, which act as preferential nucleation sites during solid state transformations.

The principal consequences of such differences are a greater hardenability for non recrystallyzed austenite and noticeable changes in the final microstructure and mechanical properties. This has been proved for predominantly pearlitic DI [3]. The authors are currently studying ways to improve mechanical properties of dual phase ADI (ausferritic-allotriomorphic ferrite matrices) by controlling the amount and distribution of this type of ferrite, as shown in Figure 4.

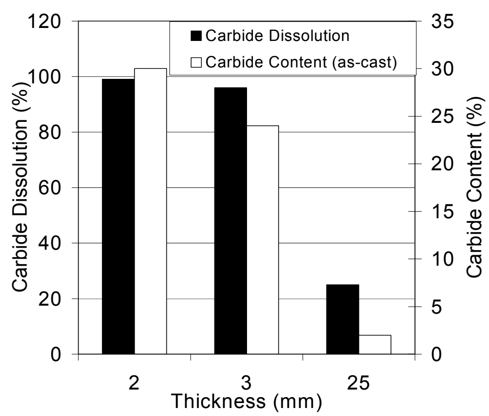

Figure 3: initial carbide content and % of dissolution.

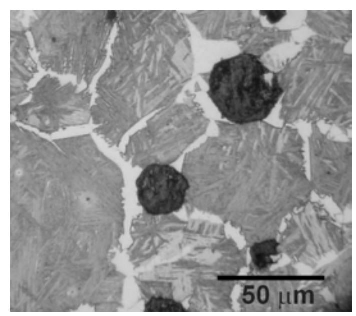

Figure 4: DI sample heat treated to produce ADI with a fine network of ferrite precipitated along the austenite grain boundaries.

4. CONCLUSIONS

Special macrography and color metallography techniques have provided new and conclusive evidences about the solidification mechanism of DI.

The observation of LTF regions, located among the dendritic austenite secondary arms, allows to identify the relationship of microsegregation and cooling rate (piece size) on the carbide formation and stability in both, conventional and TWDI castings.

The solidification austenite has very large grain size, while recrystallized austenite, obtained through austenitization, has much smaller grain size. The grain size affects solid state transformations, dictating the type, morphology and distribution of phases conforming the microstructure. This induces noticeable changes on mechanical properties.

REFERENCES

1. R. Boeri, J. Sikora: *Solidification macrostructure of spheroidal graphite cast iron*. International Journal of Cast Metals Research, Vol.13, pp 307-313 (2001).
2. G. Rivera, R. Boeri, J. Sikora: *Research advances in ductile iron solidification*. AFS Transactions, Vol. 111, 3-159, pp 1-11 (2003).
3. J. Sikora, R. Boeri: *Solid state transformations in ductile iron - influence of prior austenite matrix microstructure*. Int. Journal of Cast Metals Research, 11, No. 5, pp 395-400 (1999).
4. D. Stefanescu: Metals Handbook, Vol 15, p.172. ASM International (1988).
5. Rivera, R. Boeri, J. Sikora: *Influence of the inoculation process, the chemical composition and the cooling rate, on the solidification macro and microstructure of ductile iron.* Int. Journal of Cast Metals Research, Vol. 16 No 1-3, pp 23-28 (2003).
6. J. Massone, R.Boeri, J. Sikora: *Solid state transformation kinetics of high nodule count ductile iron*. Int. Journal of Cast Metals Research, Vol. 16 No1-3, pp 179-184 (2003).
7. A. Giacopini, R. Boeri, J. Sikora: *Carbide dissolution in thin wall ductile iron*. Materials Science and Technology, Vol. 19, No 12, pp 1755-1760 (2003).
8. Caldera, G. Rivera, R. Boeri and J. Sikora: *Precipitation and dissolution of carbides in low alloy DI plates of varied Thickness*. Submitted to Scripta Materialia (2004).