Abstract

Austempered ductile iron (ADI) castings have a wide range of application areas in engineering designs due to its promising mechanical properties and lower cost. ADI has very good strength and toughness values at the same time its ductility is relatively high compared to most of the other cast irons. This combination of high strength and toughness provides an excellent solution especially for the pieces experiencing high dynamic loads. In order to maintain these ideal mechanical properties, the microstructure and specifically the variation in the nodularity of the spheroidal graphite should be systematically controlled. The present study aims at performing quantitative and qualitative analysis of nodularity of the different ADI casting lots with respect to ASTM E2567 by digital image processing methods. Moreover, the mechanical properties of those lots were also characterized with simple tension test by means of which the dependence of nodularity on mechanical properties is tried to be clarified.

1. Introduction

Austempered ductile iron (ADI) is a specific type spheroidal graphite cast iron (SGCI) grade which has attractive mechanical properties such as high tensile, fatigue strength, toughness and relatively good ductility. The grey cast iron, which is a widely-used engineering material, can have maximum 400 MPa ultimate tensile strength (UTS) values due to flake type of graphite. The flakes promote notch-effect and reduce ductility as well [1]. However if the graphite shape can be changed to a spheroidal or nodular form with some special casting techniques the UTS may reach to 800 MPa [2]. Further improvement of mechanical properties is possible by applying heat treatments, such as austempering, that change the matrix microstructure. The excellent mechanical properties of ADI, in particular the favorable combination of high tensile strength, wear resistance and ductility, predestine this material to act as a substitute for forged or case-hardened materials and Ductile Iron (DI) [2]. ADI also offers some technical advantages on engineering components such as, being weightless and damping vibrations. ADI has been recommended to replace forged automobile components, including crank shaft, connecting rod, cam shaft, timing gear set, piston, suspension etc, [2-7]. These recommendations and the technical advantages rely on systematic controlling of the graphite nodularity and the matrix microstructure. The present study aims at performing those systematic analysis on ADI samples from 2 different lots, which showed different tensile behavior.

2. Experimental Procedure

In this study two ADI samples exhibiting different mechanical properties were subjected to detailed quantitative metallographic examination. The first sample (denoted as D1), cannot satisfy the mechanical properties stated in ISO 17804 [8], whereas the second one (denoted as D2) conforms this standard.

For metallographic examinations the specimen preparation started by sectioning the specimens via Struers Secotom-10 precision cut-off machine and by EDM technique. Afterwards, the specimens were subjected to mechanical grinding using SiC grinding papers followed by mechanical polishing using 9, 3 and 1 μm diamond paste and lastly by 0.05 μm-diameter colloidal silica particles.

The characteristics of graphite size, shape and distribution were investigated by quantitative analysis of optical micrographs taken with Nikon Eclipse LV 150 optical microscope using bright field illumination and cross-polarized light. 20 optical micrographs were taken from the as-polished state of each specimen to visualize and quantify the shape of graphite particles clearly. For each specimen more than 2500 graphite particles were analyzed. The nodularity of the graphite were evaluated in accordance with the ASTM E2567 standard [9].

The polished samples were etched with picral (4 gr. Picric acid and 100 mL ethanol) solution to examine the matrix microstructure using Zeiss MERLIN field
emission scanning electron microscope (FEG-SEM). Moreover, an average hardness value was measured from at least 5 indentations per specimen using Zwick/Roell ZHV 10 instrument using a load of 9.807 N applied for 10 seconds.

3. Result and Discussion

Figure 1 represents the micrographs of the specimens. The optical micrographs indicate the size, shape and distribution of the spheroidal graphite. In both specimens most of the graphite is in nodular form. It should be noted that the optical micrograph of specimen D2 shows some variation of color intensity in the graphite particles; since it is taken with cross-polarized light. The SEM micrographs shows the details of the matrix phases. Both specimens’ matrix is composed of mixture of bainite (B), martensite (M) and retained austenite (A). D1 specimen has more martensite and retained-austenite. The bainitic structure of D2 is finer. The martensite-austenite mixture of D1 specimen is in the form of coarser particles; whereas in D2 those structures are very finely distributed in-between the bainitic structures.

The optical micrographs in Figure 1 are taken at 100x magnification and show the graphite as almost perfect circular particles. The SEM micrographs are taken at much higher magnification, 5000x, and here the shape of graphite particles are far from ideal circular shape. This shows that the shape of graphite particles, especially the “perimeter” depends strongly on magnification. In order to obtain reproducible results on different systems, a magnification insensitive parameter has to be used.

In the present study, the shape of graphite particles were evaluated using “maximum ferret diameter (MFD)”. This parameter can be defined as the maximum distance between pairs of parallel tangents to the projected outline of the particle. The shape factor (SF) of graphite particles were then defined as:

\[
SF = \frac{\text{Area of graphite particle}}{\pi (\text{MFD}/2)^2}
\]  

![Figure 1](image_url). Optical micrographs of the samples in as-polished condition taken at 50x magnification. Scanning electron micrographs of the etched specimens taken at 5000x magnification taken with secondary electron detector. In the SEM micrographs the microstructural features are indicated as graphite (G), bainite (B) and the martensite-retained austenite (M+A).
For a perfect circle the SF is 1, and it approaches to zero when the particle shape becomes less round.

A particle is considered as graphite if its MFD is at least 10 \( \mu \text{m} \) (size criteria). A graphite particle is qualified as “spheroidal graphite (nodular graphite) when its SF is at least 0.6 (SF criteria).

Figure 2. The shape factor (SF) distributions of the graphite particles of specimens compared

Figure 2 compares the shape factor distributions of the specimens. In both specimens the highest fraction of graphite particles have SF in the range of 0.7 – 0.8. D1 specimen has more fraction of graphite particles with shape factor less than 0.6.

Using shape factor (SF), the percent nodularity of the ADI samples were compared. The “percent nodularity” can be defined by area, where the total area of spheroidal graphite particles (i.e. particles meeting the size and SF criteria) is divided by the area of graphite particles (i.e. particles meeting only size criteria). In the same manner, percent nodularity can be defined by number where total number of spheroidal graphite particles is divided by total number of graphite particles. Figure 3 compares the percent nodularity of the specimens. Although the percent nodularity by area is almost the same for both specimens, the percent nodularity by number is considerably higher in specimen D2. Moreover, the percent nodularity of D2, is same for both number and area based definitions. In specimen D1 percent nodularity by number is less compared to nodularity by area. The size distributions of the graphite particles could cause this difference.

Figure 3. The percent nodularity of the specimens compared. Both definitions of the nodularity, by area and by number is used.

Figure 4. Average size of all graphite particles (particles meeting size criteria) compared to size of spheroidal graphite particles (particles meeting both size and SF criteria) for both specimens

Figure 5. Area fractions of all graphite particles (particles meeting size criteria) compared to spheroidal graphite particles (particles meeting both size and SF criteria) for both specimens.

Figures 4 and 5 compares the average size and area fraction of graphite and spheroidal graphite particles. The area fraction of graphite is about 20%, and area fraction of spheroidal graphite is about 10% higher in specimen D2. Moreover, the average size of graphite particles is larger in specimen D1.
Specifically the average size of spheroidal graphite particles in D2 is one third smaller than that of D1.

To sum up, the graphite particles in specimen D2 is finer and more spheroidal. Moreover, the area fraction of graphite particles is considerably more in D2. These morphological features of graphite enhance the mechanical properties D2 and this specimen conforms the mechanical properties specified in ISO 17804 [8]. Moreover, the finer matrix of D2, which produces adequate hardness (see Figure 6) with improved ductility, is another important microstructural aspect.

**Figure 6.** The Vickers hardness (HV2) values of the matrix of the specimens compared.

It should be noted that the presented study makes a comparison based on specimens much smaller than the casting. Nevertheless, the specimens were taken from identical locations. The casting process, in contrast to other metal forming operations, is prone to produce heterogeneous microstructures. Therefore, for critical applications the location and the number of specimens should be addressed.

### 4. Conclusion

The evaluation of microstructure of two different ADI lots with different tensile behavior was studied. The following conclusions could be drawn:

- The nature of both the graphite nodules and the matrix effect the mechanical properties.
- The fraction, morphology and hardness of matrix phases influence the mechanical properties.
- The size, shape, fraction and nodularity of graphite particles are important.
- Changing imaging magnification strongly influences the detected “perimeter” of graphite particles. Therefore, a perimeter independent parameter is crucial for accurate identification of nodularity.
- Graphite particles with higher nodularity distributed evenly on a finer bainitic matrix produces required mechanical properties.

### 5. References