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Spatial distribution and spheroidicity characterization of graphite nodules based on morphological tools

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ABSTRACT

In this paper, the concept of compacity curve was introduced to characterize the spatial distribution of nodules which is a stronger concept than the nodular density itself. This notion was defined according to the concept traditionally known as granulometry by openings. The compacity, which is represented by polynomial curve, is obtained by the granulometric function which refers to the mean of the spatial distribution of curves. Furthermore, the nodular spheroidicity was measured in a simple way by using the conditional bisector transformation. Hence, if the conditional bisector of a nodule is composed of only one connected component, then the nodular shape is similar to a circle. Also, it was noted that the proposed methodology can distinguish between overlapping or touching nodules. The spheroidal graphite together with compacity curves allows a better description of the ductile cast iron quality by image analysis. Both criteria have been computed using the basic morphological tools as the opening, erosion and dilation. The metallographic images were obtained from the mechanical parts employed in the automotive industry, and the results were compared with other reported methods. From the compacity curve it is possible to establish that the quality of the ductile iron cast is better when it trend to have a similar shape to the normal curve.

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1. Introduction

The knowledge of the microstructure in metals is a critical factor in order to understand better the behavior of cast iron materials under different conditions. Indeed, microstructure characterization is a very important task before the use of a specific metal (Maropoulos et al., 2004). Graphite nodules are features in foundry engineering since they establish mechanical properties such as fracture toughness, impact toughness, yield and tensile strength as demonstrated (Gonzaga and Fernández, 2005). There are research works that have demonstrated that the relationship of the mechanical properties can be determined by the size and shape of nodules. For instance, Karl-Fredrik and Vratko (2009) have studied the behavior of ductility according to the size and shape of casting defects in the microstructure. Xin et al. (2009) have shown the effects of nodules shape relating with the crack initiation and crack propagation rate. Nabil et al. (2009) have investigated how to get a 100% nodular and the relationship between hardness and tensile strength.

On the other hand, recent researches have shown that the space between nodules and nodular distribution can modify the mechanical properties. Jeong-Du and Jueng-Keun (2006) have related the distance between nodules and the fatigue failure. Dommarco et al. (2006) have shown that the behavior of thin wall castings depends on the number of nodules in the microstructure. Stokes et al. (2007) studied the initiation and growth of crack through the space between nodules. Sosa et al. (2009) proposed a relationship between the residual stresses with nodule count. David et al. (2004) showed that the uniform distribution improves thin wall nodular cast. Borrajo et al. (2002) show the distribution of nodules in thin castings depending on the thickness and nodular distribution changes. In the studies of the aforementioned cases, they mention that nodular density is critical.

They use standard methods to evaluate nodularity and nodular density. Nowadays, graphite measurement and the percentage of nodularity are qualitative measurements which are determined by comparing against a pattern of the structure. Each method has a chart pattern in order to do a comparison; for example, the AFS 5-J (2000) reference provides a precision of ±10%, whereas the standard ASTM A 247 characterizes graphite particles by numbers and letters in metallographies allowing an estimation of their sizes and distribution. The standard ISO 9451-1 characterizes the particles of graphite into six types (see Fig. 1). For instance, this method cannot

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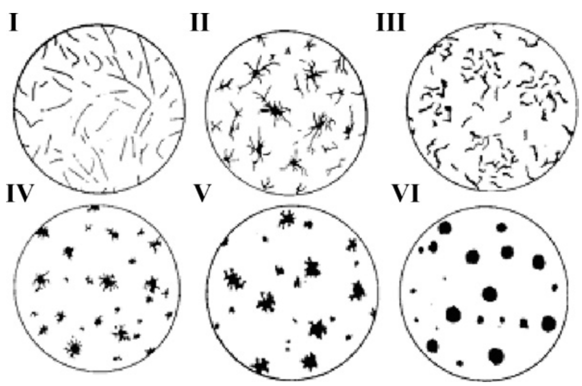

Fig. 1. Graphite particles classified by shape (ISO 9451-1).

be used to control the nodularity in the process of motor monoblock foundry (Dawson and Schroeder, 2004). A comparative study of the nodularity rate using different methods (JIS, manual count and image analysis) was carried out by Baron and Lucas (2005). Due to the assorted data in this study, it was difficult to get to a final conclusion. Moreover, the measurements did not show a trend between the results given by different laboratories or methods. The only method that shows similar results is when the image analysis is applied.

Several papers have been developed to classify the different morphologies of nodules. Li et al. (2000) determined the parameters to describe the nodular shape and incorporate the fractal geometry to get a better description of the irregular geometry of nodules. Ruxanda et al. (2002) proposed to determinate the spheroidicity by established the nodularity relationship area with perimeter. Ohser et al. (2003) provides a number of morphological parameters to classify different graphite flakes with the same six types shown in Fig. 1. Recently, Imasogie and Wendt (2004) established an index to assess the nodular form of compacted graphite iron (CGI), in accordance with international standards. De Santis et al. (2008) developed a quantitative analyzer to determine the nodular degree. They segmented the nodules with the procedure based on a method of active contours; then, they estimated shape parameters as area, eccentricity and solidity.

2. Objective

To classify the degree of spheroidisation is a tough task even for the most experienced engineers. Also, to determine the spatial distribution convert the characterization of the material in a very complex task. Thus, it is highly desirable to apply automatic classification techniques to provide a more objective and quantitative characterization, avoiding the use of the chart pattern. The present paper is aimed to develop a novelty methodology based on morphological image processing to characterize graphite nodules in ductile cast iron. Two parameters are used to characterize the graphite nodules, the nodularity and the spatial distribution which is a different concept from the nodular density. The spatial distribution is represented by a curve instead of the single value. This mean value of the spatial distribution curve will be called as a compacity curve.

Currently, the computation of the nodularity is based on how approximated the nodules shape to a circle are. For instance, a sample of graphite is less nodular when the shape of the graphite nodules does not tend to be a circle. The chart patterns are ideal standard models of comparison. This makes the characterization process of nodularity inaccurate. In consequence, the decision to classify which class of nodule is a criterion that depends on visual perception of the evaluator.

Another measurement is the density of nodules which is defined as the number of nodules per unit area. The chart patterns ASF, allows to estimate how many nodules are per unit area; however, the smallest error is ±25 nodules and the largest error is ±100 nodules.

The above works present the nodular density as a number of nodules per square millimeter which is not enough to characterize the nodular spatial distribution. In consequence, it does not have a reliable measurement for all the cases. In the proposed methodology, the spatial distribution of nodules is characterized by a granulometric study made on the ferritic matrix.

3. Methodology

To get appropriate images, the sample preparation defined by the standard ASTM (2001) was followed. The images were acquired with a Nikon epiphot 200 optical metallographic microscope which is equipped with integrated video system and frame grabber (Mutech 460).

To determine the nodularity of nodules, the notion of conditional bisector which determines the skeleton of the nodules was applied. Based on this, when the nodule shape is close to a disk, its skeleton is a point. In an opposite case, the skeleton of nodules of the classes I–V (see Fig. 3) is composed of several segments. Finally, to compute the spatial distribution, the concept of granulometry by morphological openings was applied. The spatial distribution or spatial compacity has not been studied.

3.1. Basic morphological tools

Morphological filters are increasing and idempotent transformations (Serra, 1988; Soille, 2003). While the increasing property expresses that the order is preserved, one says that a transformation T is idempotent if and only if for all function f, $T(T(f)) = T(f)$. The basic morphological filters are the morphological opening $\gamma_{\mu B}$ and the morphological closing $\varphi_{\mu B}$, B is an elementary structuring element (3 × 3 pixels) that contains its origin. $\widehat{B}$ is the transposed set $\left(\widehat{B} = \left\{-x : x \in B\right\}\right)$ and μ is an homothetic (scale) parameter. In this work, the homothetic parameter takes only integer values. The morphological opening is an anti-extensive filter and the morphological closing an extensive filter. The morphological opening and closing are given, respectively, by

$$\gamma_{\mu B}(f)(x) = \delta_{\mu B}(\varepsilon_{\mu B}(f))(x) \tag{1}$$

$$\varphi_{\mu B}(f)(x) = \varepsilon_{\mu B}(\delta_{\mu B}(f))(x) \tag{2}$$

where the morphological erosion $\varepsilon_{\mu B}$ and dilation $\delta_{\mu \beta}$ are expressed as $\varepsilon_{\mu B}(f(x)) = \wedge\left\{f(y); y \in \mu \widehat{B}_x\right\}$ and $\delta_{\mu B}(f(x)) = \vee\left\{f(y); y \in \mu \widehat{B}_x\right\}$, where $\wedge$ is the *inf* operator ($\vee$ is the *sup* operator). Another class of filters is composed by the opening and closing by reconstruction. These filters are built using the geodesic dilation and erosion. Where the geodesic dilation and the geodesic erosion of size one are given by $\delta_f^1(g) = f \wedge \delta_B(g)$ with $f \leq g$ and $\varepsilon_f^1(g) = f \vee \varepsilon_B(g)$ with $f \leq g$, respectively. These basic geodesic transformations, the geodesic dilation and the geodesic erosion of size one, are iterated until idempotence is reached to build the reconstruction transformations defined by

$$R(f, g) = \underbrace{\delta_f^1 \ldots \delta_f^1 \delta_f^1(g)}_{until\ stability} \tag{3}$$

and

$$R*(f, g) = \underbrace{\varepsilon_f^1 \ldots \varepsilon_f^1 \varepsilon_f^1(g)}_{until\ stability} \tag{4}$$

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