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METHODOLOGY FOR DETERMINATION OF DEGREE OF NODULARITY IN A DUCTILE CAST IRON GGG 40 BY ULTRASONIC VELOCITY TEST

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ABSTRACT

Cast iron alloys combine many elements such as carbon, iron, silicon, magnesium and can be usually classified according to their microstructure in ductile, gray, compacted, white, and malleable. Each one has particularities in terms of properties and applications. Hence, this study aims to evaluate the degree of nodularity (%) in a ductile cast iron alloy GGG 40. In this context, a methodology to investigate the degree of nodularity was proposed. The ultrasonic method was used to determine the amount of ductile graphite as well as for parts release and thus facilitated the industrial operational execution. The effect of ultrasonic sound was investigated in sixty-seven ductile cast irons, and these analyses were further compared to the level of nodularity observed by metallography. Finally, based on the findings, the cast iron quality was guaranteed, leading to time-savings, avoiding the microstructural examination, and thus promoting cost reductions.

Keywords: *degree of nodularity, ductile cast iron, ultrasonic velocity test.*

1. INTRODUCTION

Ductile iron alloys have a highlighted position among all the other cast irons. One of its characteristics is to present carbon in the spheroidal graphite form (Skaland, 1993) to promote enhanced mechanical strength and ductility, which are essential properties in their practical applications. Their chemical composition is similar to the gray cast iron, containing more than 2% carbon. In particular, its spheroidal graphite is influenced by the magnesium addition, which is the nodularizing agent. Still, other elements may help in improving graphite shape (Davis, 1996; Guesser, 2009). One of the main problems faced by quality control in a foundry (cast iron) industry is to ensure that the product will not present an unwanted microstructure, the degree of nodularity is acceptable, and the parts can be used without problems (Wilccox, 2003). Several analyzes can be used for evaluating the cast iron quality and, often, microstructural evaluation is the first choice. However, for optimizing the manufacturing process, this analysis can be replaced by the ultrasonic test, providing higher efficiency and decreasing the material and time consumption.

The ultrasonic testing, although widely used in carbon steels, it was not yet commonly applied to cast irons (Wilccox, 2003). However, the production of ductile cast irons has grown in recent years. Therefore, in this field, these cast irons present some advantages, such as low manufacturing cost and easy fabrication (Herrera *et al.* 2013; Souza *et al.* 2014). As mentioned in (Gevaerd, 2007), the sonic velocity is a non-destructive test for analyzing cast irons, making it possible to correlate the microstructure with the sound propagating in the material. Being a versatile process, it can allow the release of large batches in reduced time. In this context, the sound velocity in a material depends on its microstructure, and there may be better or worse conditions for propagation. In addition, it should be noted that the graphite spheroidal shape presents less resistance to the passage of sound since the wave deflection is smaller (Gevaerd, 2007). Moreover, an error in Mg incorporation during the nodularization may lead to an unwanted structure. Hence, if the part presents a low sonic velocity, its inadequate degree of nodularity may lead to fracture due to insufficient material's strength. In this sense, some authors (Nabil, 2009) have mentioned that the main factors affecting the cast iron mechanical properties are related to its microstructure.

The industrial matter of this study was to release parts with an adequate microstructure and, consequently, to avoid the metallography step. Hence, for the parts to be approved, the degree of nodularity shall be greater than 80% (ASTM A247-17, 2017). This ductile graphite amount corresponds to a sonic velocity of 5595 m/s (Gevaerd, 2007), but for safety reasons, it is suggested that this sonic velocity shall be of 5603 m/s. On the other hand, when the evaluated samples reach sonic velocity values lower than it, a complementary microstructural evaluation is recommended.

2. MATERIALS AND METHODS

The chemical analyses were carried out in the optical emission spectrometer, as can be seen in Figure 1. Therefore, sixty-seven samples were taken into consideration.

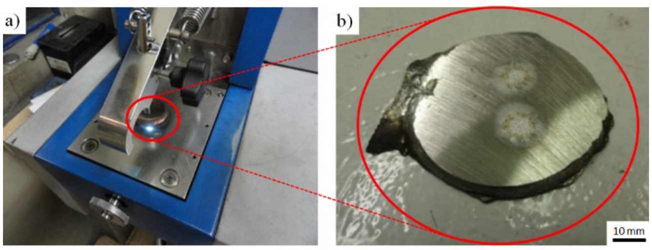

Figure 1. *a) Spectrometer, b) Sample.*

The study of sonic velocity and its relation with the degree of nodularity was performed in many specimens. The samples were randomly taken from batches, during the metal casting at a given fading time. In this context, Figure 2 a) presents the ultrasonic equipment used. The sonic velocity test was performed on specimens, as it is shown in Figure 2 b).

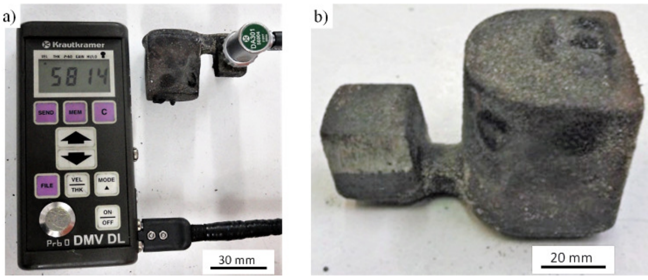

Figure 2. *a) Ultrasonic apparatus for sonic velocity test, b) Test specimen.*

The equipment, Krautkramer DMV DL Digital Ultrasonic Velocity Gauge, measures the pulse transit time and calculates the velocity (V) in which the sound propagates in the material as indicated by Equation 1. For correct measurements, it is important to know the sample thickness. After measuring the sonic velocity, a value that must guarantee a degree of nodularity higher than 80% is obtained and thus generating reliability in the desired microstructure.

$$V = \text{Distance travelled / Time [mm/s]} \qquad \text{(Eq. 1)}$$

For microstructural observation, samples were prepared by sample cutting, sandpaper, polishing, and then etched by Nital (2%). These samples were taken from sonic velocity specimens (Figure 3) and specific fading time, which was ranging from 8 to 10 minutes. Finally, the images were evaluated by Digimess software for verifying the level of nodularity.

Figure 3. *A test specimen for metallography.*

For tensile tests, cylindrical specimens were machined with Lo= 25 mm, as suggested by DIN 1563:2003 (DIN EN 1563, 2003), with dimensions as demonstrated in Figure 4. Hence, the mechanical tests were performed on an EMIC brand machine, according to ISO 6892 (NBR ISO 6892, 2013).

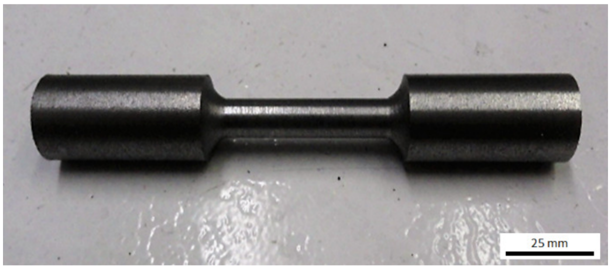

Figure 4. *A test specimen for the mechanical test.*

3. RESULTS AND DISCUSSIONS

Microstructural results, related to the degree of nodularity, sonic velocity and Mg content (%) for selected samples (6 samples with a degree of nodularity below 80%, and 6 samples with a level of nodularity greater than 80%) are shown in Figures 5, 6, 7 and 8. As different degrees of nodularity were obtained, they were classified into adequate (above 80%) and non-conformed (below 80%). In this sense, Figures 5 and 6 present the approved ductile cast irons, while Figures 7 and 8 display the unapproved ones, according to the methodology proposed. As reported in (Gevaerd, 2007), a sonic velocity of 5595 m/s caused a degree of nodularity of 80%, a fact which has a good agreement with the present study.

Figure 5 shows the cast iron microstructure in the spheroidal form and small-sized nodules. As the sonic velocity decreased (from 5662 m/s to 5641 m/s), the degree of nodularity decreased (from 91% to 86%). On the other hand, as can be seen in Figure 6, in general, as the sonic velocity decreases (from 5629 m/s to 5595 m/s), the level of nodularity increased (from 84% to 88%). This fact may be related to the Mg (%) content, which was shown to be variable in the samples (Figures 6 a), b) and c)).

Considering Figures 7 and 8, which present samples with a degree of nodularity below 80%, more heterogeneous microstructures were observed (in relation to graphite nodules). Moreover, Figure 7 shows nodules in different sizes and shapes. In addition, it was observed that as the sonic velocity decreased (from 5570 m/s to 5604 mm/s), the degree of nodularity decreased (from 75% to 48%), a fact that may be related to the nodules shape, some compacted and also veins. In fact, the graphite veins shape (also called graphite flakes) can act as a stress concentrator and maybe not favorable to the cast iron properties (Rudnev, 2018). Moreover, as verified in (Čanžar, 2012), the larger irregularly shaped nodules would promote unfavorable fatigue properties. Still, Figure 8 shows microstructures with similar behavior, where at a sonic velocity of 5017 m/s and Mg content of 0.008%, the lowest level of nodularity was achieved (17%).

Figure 9 presents a correlation between sonic velocities and degrees of nodularity. In this context, when the level of nodularity was greater than 80%, the sonic velocity values were close to the trend line (without great dispersion in the results). Conversely, for degrees of nodularity below than 80%, a greater difference was observed between sonic velocity values and levels of nodularity indicated by the trend line.

From the data presented in Figure 9, the means of the measurements were used to determine an equation that corresponds to the tendency observed in this work. Hence, Equation 2 represents these results. In this equation, the percentages of nodularity to obtain sonic velocities were applied (in the range of 17 to 100%). Thus, the approved samples (degree of nodularity above 80%) are presented in Table 1. From the practical foundry (cast iron) industry viewpoint, it can be revealed that this equation has been already used as a procedure for parts release.

$$y= -842{,}23x^3 + 1857{,}2x^2 -693{,}68x + 5393{,}3 \quad \text{(Eq.2)}$$

Figure 10 shows the correlation between the degree of nodularity (above 75%), (a) Ultimate Tensile Strength, (b) Elongation, and (c) Yield Strength. In general, as can be observed, these results showed that an increase in the degree of nodularity led to enhanced mechanical properties. On the other hand, for degrees of nodularity smaller than 75%, there was a large variation in the mechanical properties. Therefore, it indicates an inadequate microstructure and, consequently, these findings were not reported at this point.

Based on the current findings, the ductile cast iron batch release was done, considering a specified degree of nodularity of at least 80%, since it corresponds to the sonic velocity of 5595 m/s (Gevaerd, 2007). However, for safety reasons, it is suggested that the release shall be executed when sonic velocities higher than 5603 m/s are observed, applying the highest standard deviation verified (± 8 m/s). On the other hand, for sonic velocities below 5603 m/s, it is recommended that metallographic analysis must be performed for quantifying the real level of nodularity. Finally, it should be remembered that this non-destructive method can be applied as a practice for the evaluation of the degree of nodularity and, therefore, as a means of guaranteeing the quality required by ASTM A247 (ASTM, 2017).

4. CONCLUSIONS

The results of the present work, which proposed a methodology to determine the degree of nodularity by the sonic velocity in a ductile cast iron GGG 40, can be summarized as follow:

• The validation process for sonic velocity test and level of nodularity determination was important to obtain reliable results and subsequent release of ductile cast iron parts with reasonable quality.

• The nodular cast iron parts can only be released when sonic velocity higher than 5603 m/s are observed. For sonic velocities below of its value, it is necessary to observe the microstructural features in order to verify the real level of nodularity.

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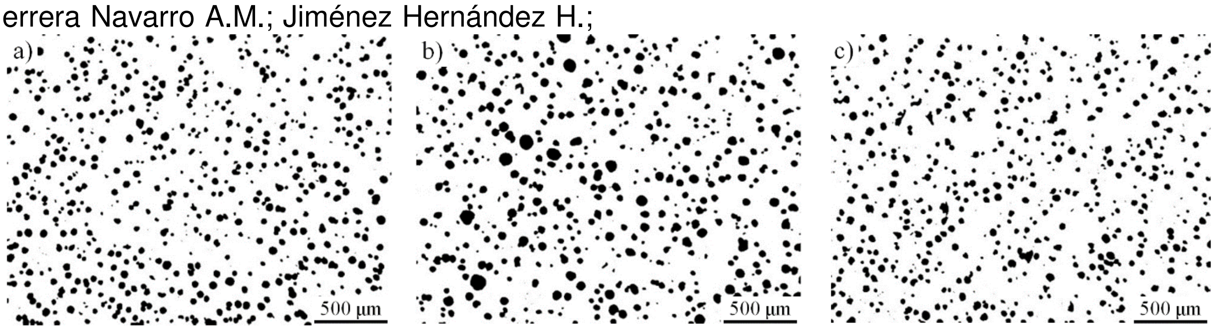

Figure 5. *a) Degree of nodularity: 91%, sonic velocity: 5662 m/s, Mg: 0.026%. b) Degree of nodularity: 88%, sonic velocity: 5650 m/s, Mg: 0.025%. c) Degree of nodularity: 86%, Sonic velocity: 5641 m/s, Mg: 0.025%. 100X.*

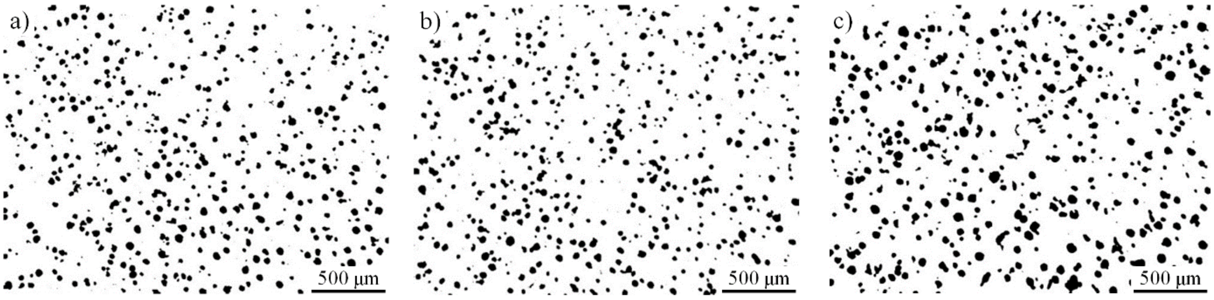

Figure 6. *a) Degree of nodularity: 84%, sonic velocity: 5629 m/s, Mg: 0.024%. b) Degree of nodularity: 82%, sonic velocity: 5610 m/s, Mg: 0.022%. c) Degree of nodularity: 78%, Sonic velocity: 5595 m/s, Mg: 0.019%. 100X.*

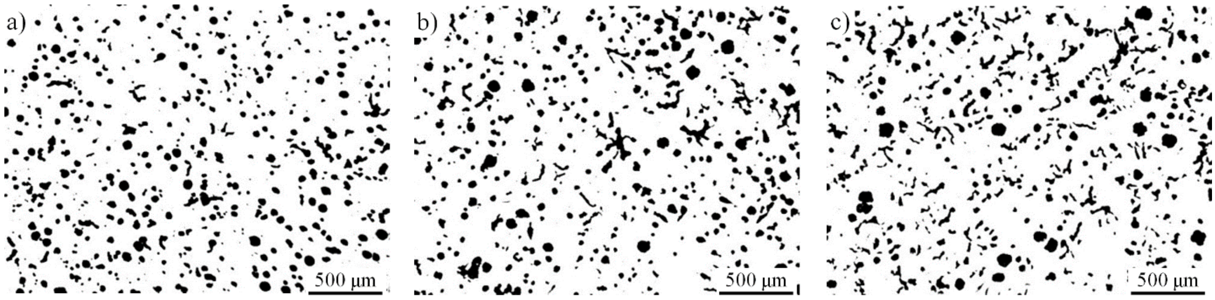

Figure 7. *a) Degree of nodularity: 75%, sonic velocity: 5570 m/s, Mg: 0.016%. b) Degree of nodularity: 65%, sonic velocity: 5462 m/s, Mg: 0.017%. c) Degree of nodularity: 48%, Sonic velocity: 5404 m/s, Mg: 0.016%. 100X.*

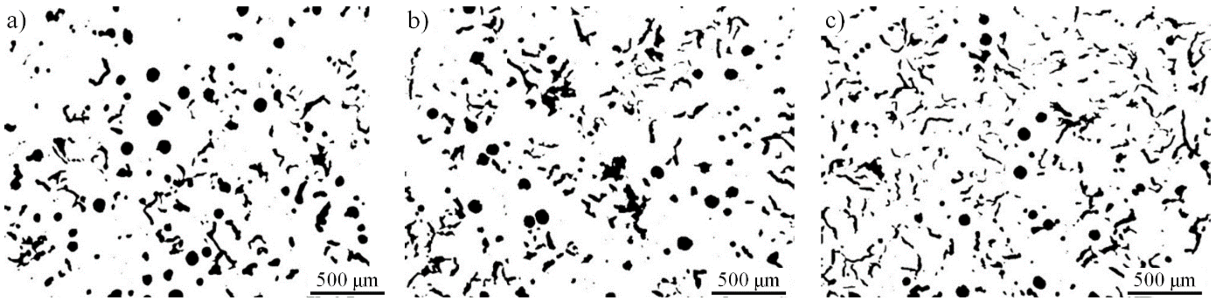

Figure 8. *a) Degree of nodularity: 45%, sonic velocity: 5373 m/s, Mg: 0.018%. b) Degree of nodularity: 33%, sonic velocity: 5335 m/s, Mg: 0.008%. c) Degree of nodularity: 17%, Sonic velocity: 5017 m/s, Mg: 0.008%. 100X.*

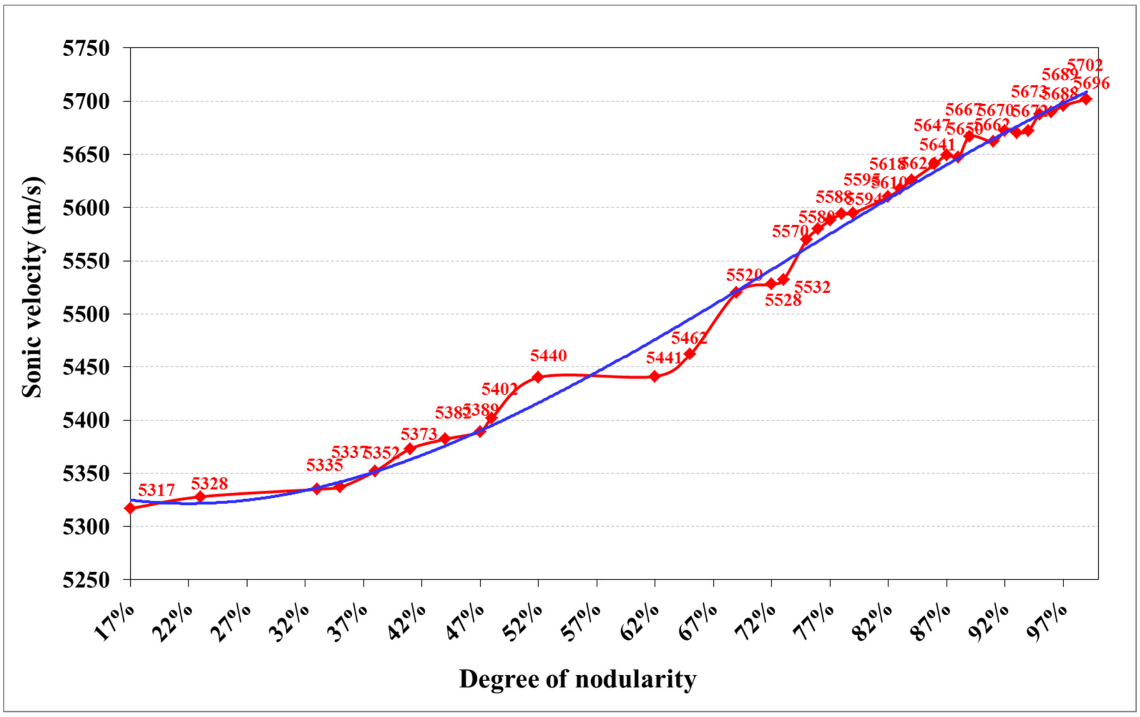

Figure 9. *Correlation between sonic velocity and degree of nodularity [%].*

Table 1. *The degree of nodularity (%) x Sonic Velocity.*

Nodularity [%]	Sonic velocity [mm/s]	Nodularity [%]	Sonic velocity [mm/s]	Nodularity [%]	Sonic velocity [mm/s]	Nodularity [%]	Sonic velocity [mm/s]
100%	5714	79%	5589	58%	5451	37%	5348
99%	5709	78%	5582	57%	5445	36%	5345
98%	5703	77%	5575	56%	5439	35%	5342
97%	5698	76%	5569	55%	5433	34%	5339
96%	5693	75%	5562	54%	5427	33%	5336
95%	5687	74%	5555	53%	5422	32%	5334
94%	5682	73%	5549	52%	5416	31%	5332
93%	5676	72%	5542	51%	5411	30%	5330
92%	5670	71%	5535	50%	5405	29%	5328
91%	5665	70%	5529	49%	5400	28%	5326
90%	5659	69%	5522	48%	5395	27%	5325
89%	5653	68%	5515	47%	5390	26%	5324
88%	5646	67%	5509	46%	5385	25%	5323
87%	5640	66%	5502	45%	5380	24%	5322
86%	5634	65%	5495	44%	5376	23%	5322
85%	5628	64%	5489	43%	5371	22%	5322
84%	5621	63%	5483	42%	5367	21%	5322
83%	5615	62%	5476	41%	5363	20%	5322
82%	5608	61%	5470	40%	5359	19%	5323
81%	5602	60%	5464	39%	5355	18%	5324
80%	5595	59%	5457	38%	5352	17%	5325

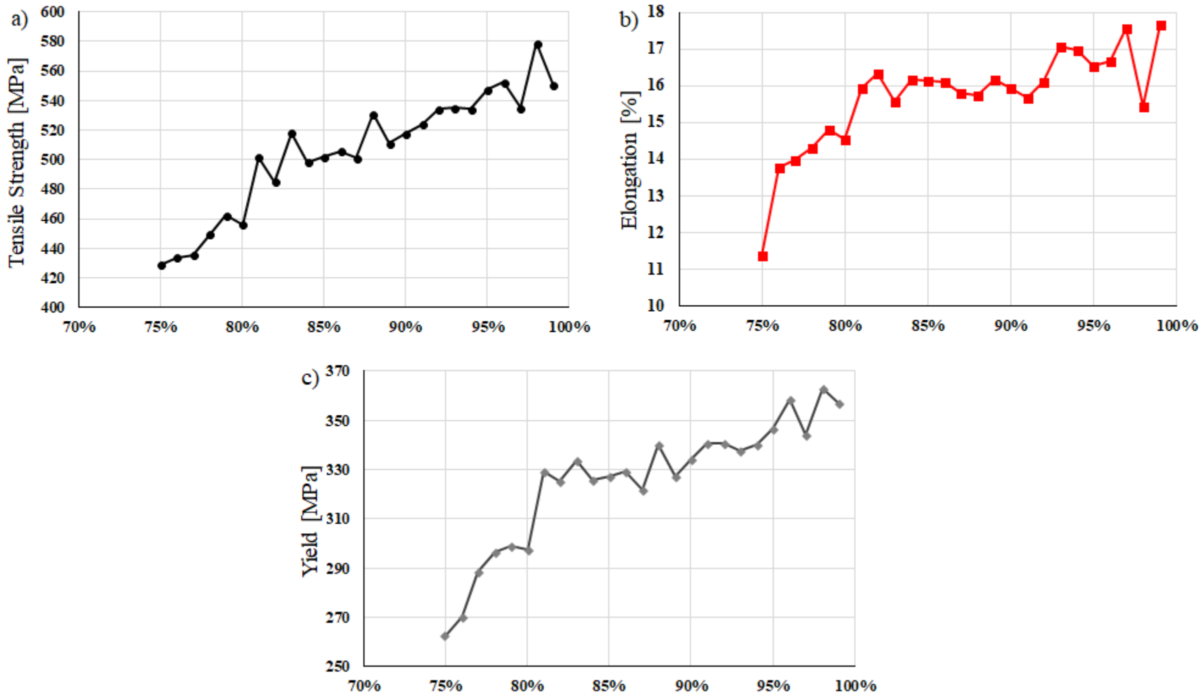

Figure 10. *Correlation between degree of nodularity and a) Ultimate Tensile Strength, b) Elongation, and c) Yield Strength.*