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WEAR BEHAVIOR CHARACTERIZATION AND ANALYSIS OF CAST AUSTEMPERED DUCTILE IRON (ADI)

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Abstract. *The austempered nodular cast iron (ADI) is a material with excellent mechanical properties such as high tensile strength, good toughness and ductility and high resistance to fatigue and wear. These characteristics arises from its unique microstructure after undergoing austempering heat treatment, forming acicular ferrite(ausferrite) and retained austenite with dispersed graphite nodules. The low cost of production combined with these properties have made this material particularly suitable for the production of components for various industries, especially automotive and agricultural. In this work a pearlitic nodular cast iron alloyed with copper was subjected to austempering heat treatment at three temperatures (240, 300, and 360 °C). Each sample was characterized by metallographic testing, hardness and adhesive wear on "calotest" type machine. Based on the results, it was found that the ADI austempered at 240 ° C had the finest structure among the samples, since the lower austempering temperature results in a higher austenite cooling rate and a lower rate of diffusion of carbon when forming ausferrite, what also raises the hardness of the material. The opposite effect occurs for the highest austempering temperature, where the diffusion rate of carbon is higher, thus developing upper ausferrite. With respect to wear, the ADI showed higher strength than the ductile iron standard. Interestingly, the wear performance (lost volume x distance) of all ADI samples converged to a single value in the course of the tests.*

Keywords: *ductile iron, austempering, ADI, adhesive wear.*

1. INTRODUCTION

Austempered nodular cast iron (ADI) constitute the latest development in the family of nodular cast iron. The ADI austempering heat treatment produces a unique microstructure among cast irons, composed of acicular ferrite and retained austenite (ausferrite), increasing the material strength, coupled with good ductility and fracture toughness, high fatigue resistance and abrasion resistance (Kayali et al., 2010; Mattar et al., 2011; Putatunda, 2001). Another factor that influences the use of this material is economic, its production cost is lower than steel. Due to these features, the ADI is considered to be an adequate substitute for forged steel (Kayali et al., 2010; Putatunda, 2001).

The addition of alloying elements responsible for ADI hardenability is what sets it apart from conventional nodular irons. These elements are: manganese, nickel, molybdenum and copper (Ahamadabadi et al., 1999; Putatunda, 2001).

The austempering heat treatment of ADI occurs in two stages. The first is austenitizing in the range between 850 at 950°C and the second is an isothermal treatment between 230 and 400 ° C, when the transformation of austenite to acicular ferrite and retained austenite takes place (Erić et al., 2006; Putatunda, 2001).

The ADI is well accepted in the automotive industry, allowing high vibration absorption, considerable weight reduction (10% lighter than steel) combined with high wear and deformation resistance and preventing malfunctions under unpredictable unfavorable working conditions such as a momentary failure of a lubrication system. Some examples of manufactured parts for automotive industry are automotive crankshafts, transmission gears, connecting rods, etc (Martins et al., 2008). Military equipment (guns, aircraft landing gear, etc.), Energy industries and mining, are also examples of the use of this material (Lu et al., 2001; Putatunda, 2001).

The aim of this study is to evaluate the behavior of the adhesive wear on three ADIs, each at a different austempering temperature. The resistance to penetration and the resulting microstructures are also analyzed.

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2. MATERIALS AND METHODS

The material used in this study is a pearlitic matrix nodular cast iron. Table 1 shows the chemical composition. Four test samples were machined to the dimensions 30 x 20 x 4 mm.

Table 1. Chemical composition of nodular cast iron with copper addition.

Chemical Element	wt%
Carbon	3.70
Silicon	2.73
Manganese	0.21
Copper	0.71
Carbon Equivalent (C+Si/3)	4.61

For the normalizing heat treatment, samples were austenitized at 950 °C. Then a sample was set apart and the other three went through the isothermal austempering treatment (molten salt) at three different temperatures: 240, 300 and 360 °C. The next step was the metallographic evaluation, for which the four samples were embedded in bakelite, ground and polished conventionally and etched with Nital 2%, for visualization of the microstructure.

An optical microscope with image analysis system was used to determine the average proportion of graphite nodules contained in nodular cast iron.

Two types of hardness tests were used, Vickers and Brinell. The first test used a 1000 gf load for the analysis of the matrix, and the second a hardened steel ball penetrator with Ø 2.5 mm and a load of 187.5 kgf to average all surface constituents (matrix and graphite nodules). For both tests, a total of 15 measurements were made for each material to obtain the averages and standard deviations.

For adhesive wear testing the micro-adhesive wear with stuck ball method was used. This essay is a "calotest" type test. The ball used in the test was hardened AISI 52100 steel with a diameter of 25.4 mm. For each specimen 4 trials times were used (5, 10, 15 and 20 minutes). The test load was 160 gf and the rotation speed was 400 rpm. The result of this test consisted of a spherical shaped cap worn region, having a geometric relationship with the ball used. Thus, knowing the diameter of the cap, the volume of removed material during the test can be determined according to Eq. (1) where V: volume removed, b: diameter of the dome shape and r: radius of the sphere.

$$V = \pi b^4/64R \quad (1)$$

3. RESULTS AND DISCUSSION

In Figure 1 is shown the normalized microstructure of the nodular cast iron with copper addition.

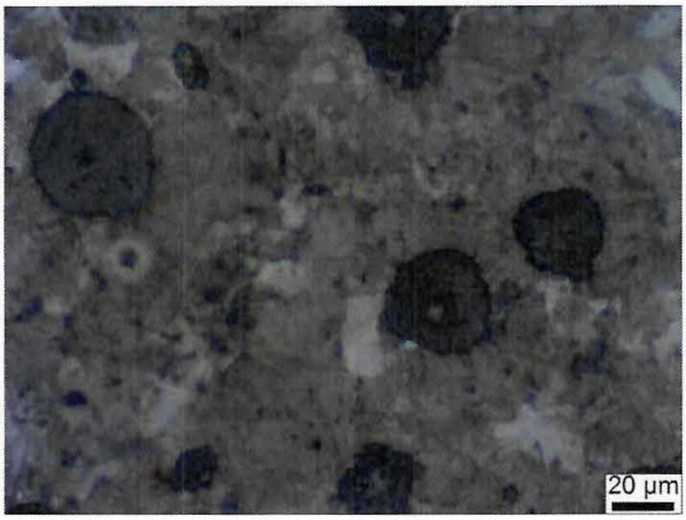

Figure 1. Nodular cast iron - normalization heat treatment at 950 °C. Attack Nital 2%. Matrix consisting of fine pearlite with graphite nodules.

Figures 2 to 4 show the optical microstructures of austempered ADI treated at temperatures of 240, 300 and 360 °C.

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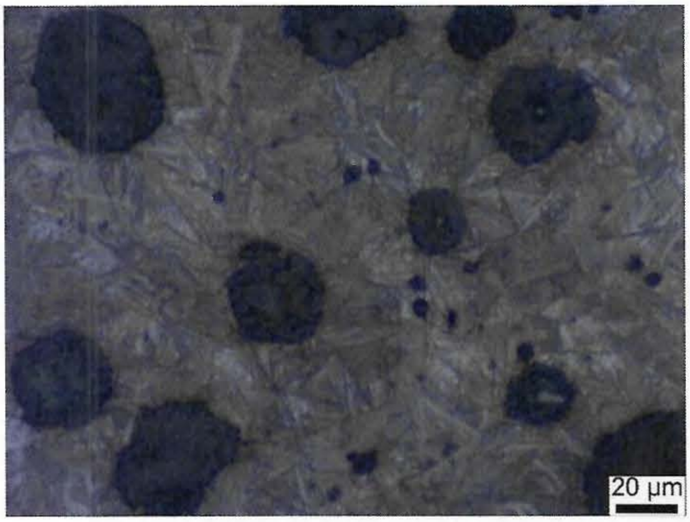

Figure 2. Austempered ADI at 240 °C. Attack Nital 2%. Matrix consisting of fine ausferrite with graphite nodules.

Figure 3. Austempered ADI at 300 °C. Attack Nital 2%. Matrix consisting of ausferrite with graphite nodules.

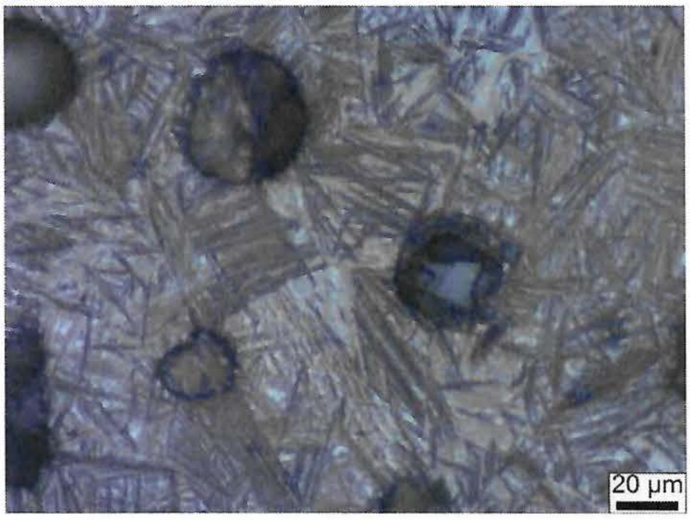

Figure 4. Austempered ADI at 360 °C. Attack Nital 2%. Matrix consisting of coarse ausferrite with graphite nodules.

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Analyzing the microstructures shown in Figs. 2 to 4, it is found that the ADI austempered at 240 °C has finer structure than the ADI austempered at 300 and 360 °C. The lower the austempering temperature, the higher the cooling rate of primary austenite and less diffusion of carbon, thus promoting the nucleation of new ferrite plates instead of its growth (lower ausferrite). The opposite effect occurs for the higher austempering temperature, where the diffusion rate of carbon is increased, favoring its growth, providing a coarser structure (upper ausferrite).

Figure 5 show the aspect of the analysis performed by the image processing program on the images obtained using the optical microscope. The result was 11.30 ± 0.82% of graphite.

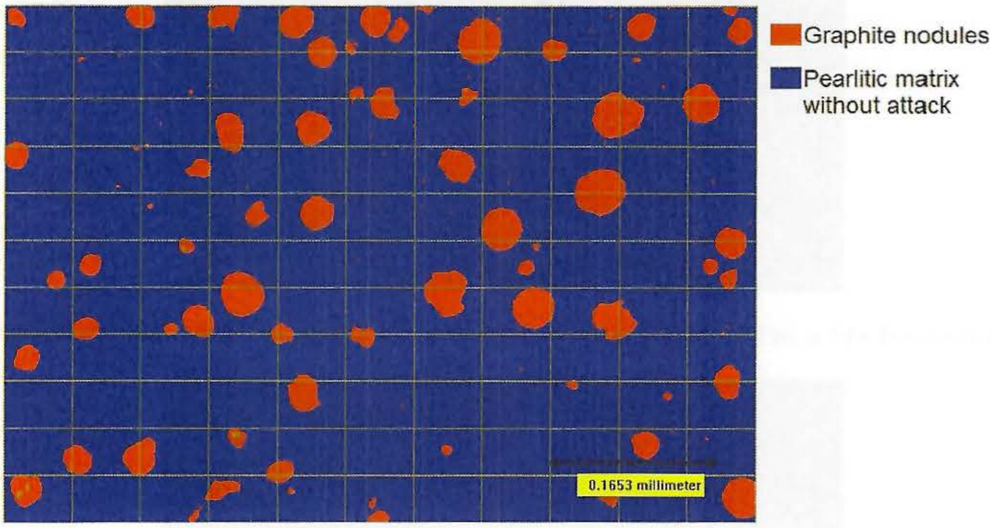

Figure 5. Quantitative evaluation of nodular graphite in cast iron. Matrix material without attack.

Table 2 shows the morphological classification of graphite in various positions of the used ingot according to ASTM A-297 (Mattar, 2009).

Table 2. Morphological evaluation of nodular graphite cast iron analyzed.

	Center	Half way	Surface
Type	I and II	I and II	I and II
Size	5	5	6
Nodules/mm^2	212	180	312
Nodularisation	85%	85%	90%

Graphite shape Type I is the most desired in nodular cast iron, although the Type II carries virtually no adverse effect on their properties and characteristics. The sizes of graphite nodules found are considered small, and this provides a considerable number of nodules per mm2. Furthermore, a better distribution of the graphite nodules favors the diffusion of carbon in austenite during austenitization, since there is a shorter distance between the graphite nodules which acts as a carbon source. The density of nodules found meets the recommendations for a ductile iron of good quality (Reesman and Loper, 1967). For Luo et al. (1995) and Zhang et al. (1993), the number of nodules per mm2 has a very important effect on the mechanical properties of the ADI and can directly affect the wear resistance.

In Tables 3 and 4 show the results of Vickers hardness (matrix only) and Brinell hardness (average of matrix + graphite nodules), respectively, for austempered ductile iron samples at various temperatures and for the sample only normalized.

Table 3. Results from Vickers microhardness.

Heat treatment	Results [HV]
Austempered at 240 °C	578.4 ± 36.4
Austempered at 300 °C	440.0 ± 34.3
Austempered at 360 °C	355.8 ± 33.3
Normalized	343.8 ± 29.8

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Table 4. Results from Brinell hardness.

Heat treatment	Results [HB]
Austempered at 240 °C	477 ± 19.7
Austempered at 300 °C	443 ± 21.6
Austempered at 360 °C	369 ± 15.4
Normalized	325 ± 28.2

From the results of Brinell hardness and Vickers microhardness it can be seen that in comparison with the standard cast iron, austempering treatment significantly increased the hardness of the matrix and matrix + nodules and that the hardness decreased with increasing austempering temperature.

Optical microscopy images presented in Fig. 6 show the interior of the formed wear cap after the 20 minute run.

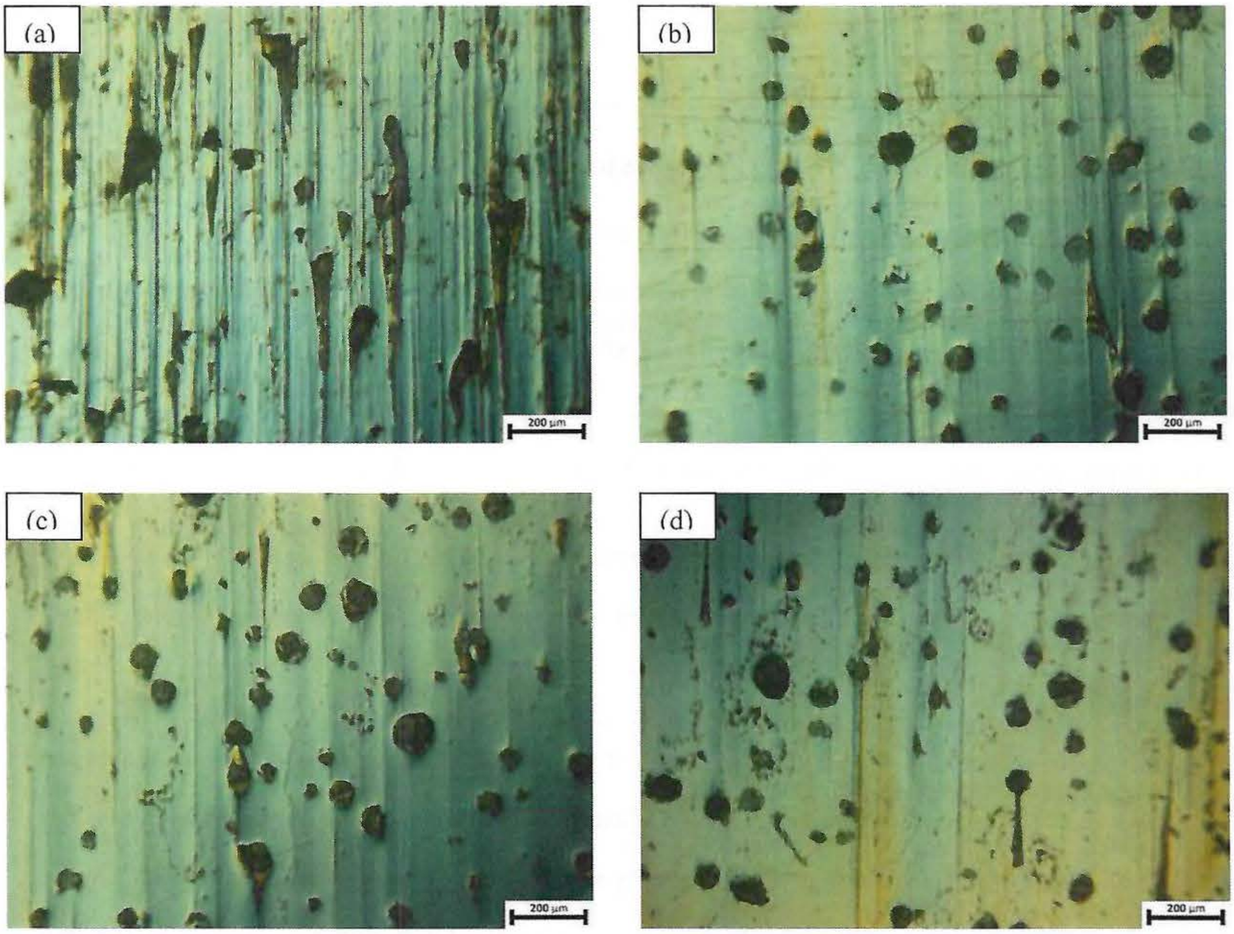

Figure 6. Aspects of the interior of the wear cap. Distance traveled: 642.11 m (20 minutes - test time). (a) normalized nodular cast iron; (b) ADI austempered at 240 °C; (c) ADI austempered at 300 °C; (d) ADI austempered at 360 °C.

The standard sample (normalized only) picture shows a characteristic surface morphology of the type two bodies abrasion wear, with the presence of the characteristic grooves. This is probably due to the detaching of material that is subsequently attached to the sphere, and begins to act as an abrasive. For the austempered samples, the wear products may have contributed to the polishing of the scratched surfaces, and to the wear behavior convergence of all three samples at the end of the test.

Therefore, the wear that was originally of the type adhesive passed to the abrasive type, for all materials tested.

Figure 7 presents the adhesive wear plot of various samples subjected to different treatments.

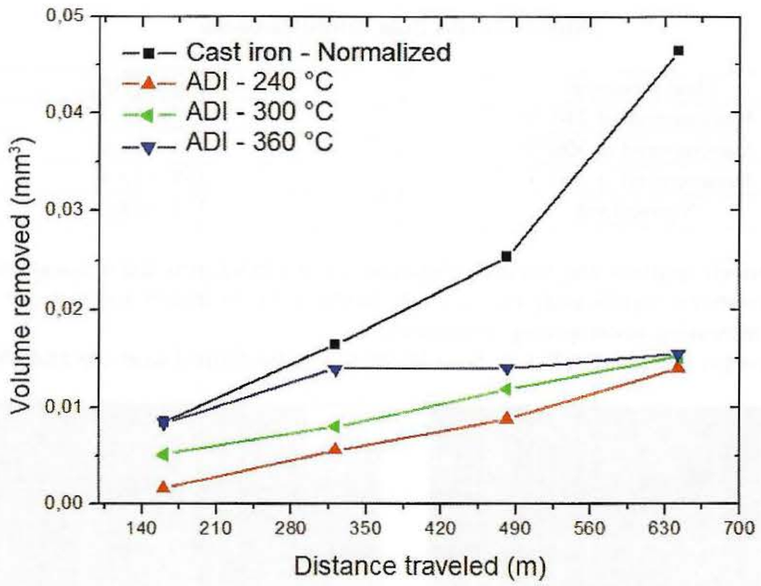

Figure 7. Plot of adhesive wear for cast iron and the three ADI samples.

Compared with the standard normalized cast iron, all three austempering treatments improved the wear resistance of the samples. Although the samples treated at lower temperatures initially presented a better performance, in the course of the trials a convergence behavior took place, and at the end, all performances were similar.

4. CONCLUSIONS

All austempering treatments were effective in increasing the wear resistance of the samples, which can increase the service life of the manufactured parts.

The wear mechanism for all samples, which was initially the adhesive type, in the course of the tests became abrasive, probably due to detachment of hard particles, which later joined the ball and started to act as abrasive elements.

For longer times of trials, there was a convergence in the wear behavior of the three austempered samples, with all of them featuring similar performances at the end.

5. REFERENCES

Ahamadabadi, M. N., Ghasemi, H. M. and Osia, M., 1999. "Effects of successive austempering on the tribological behavior of ductile cast iron". *Wear*, Vol. 231, p. 293.

Erić, O. *et al.* 2006. "Microstructure and fracture of alloyed austempered ductile iron". *Materials Characterization*, Vol. 57, p. 211.

Kayali, Y. *et al.* 2010. "Investigation of mechanical properties of boro-tempered ductile iron". *Materials and Desing*, Vol. 31, p. 1799.

Lu, Z. L. *et al.*, 2001. "An investigation of the abrasive wear behavior of ductile cast iron". *Journal of Materials Processing Technology*, Vol. 116, p. 176.

Luo, Q., Xie, J. and Song, Y., 1995. "Effects of microstructures on the abrasive wear behavior of spheroidal cast iron". *Wear*, Vol. 184, p. 1.

Martins, R., Seabra, J. and Magalhães, L., 2008. "Austempered ductile iron (ADI) gears: Power loss, pitting and micropitting". *Wear*, Vol. 264, p. 838.

Mattar, A. R., 2009, "Influência dos elementos de liga Cu-Ni-Mo nas propriedades mecânicas e na austemperabilidade do ADI". Master's degree dissertation. Universidade de São Paulo. Sao Paulo.

Mattar, A. R. *et al.* 2011. "Influence of alloying elements Cu, Ni and Mo on mechanical properties and austemperability of austempered ductile iron". *International Heat Treatment and Surface Engineering*, Vol. 5, p. 78.

Putatunda, S. K., 2001. "Development of austempered ductile cast iron (ADI) with simultaneous high yield strength and fracture toughness by a novel two-step austempering". *Materials Science and Engineering*, Vol. A315, p. 70.

Reesman, R.W. and Loper, J. C. R., 1967. "Heavy section ductile iron as affected by certain processing variables". *AFS Transations*, Vol. 67-75, p. 1.

Zhang. Y. *et al.* 1993. "Investigation of tribological properties of brake shoe materials phosphorous cast irons with different graphite morphologies". *Wear*, Vol. 166, p. 179.