EVALUATION OF ABRASIVE WEAR IN DIFFERENT TYPES OF CAST IRONS

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Abstract. *This work aims to comparatively evaluate the abrasive wear resistance of a group of nodular cast iron and a white cast iron. The material characterization was performed using optical and scanning electron microscopy. After the production and heat treatment of the samples, a rotating device with sand as the abrasive material was made and employed. In order to assess the wear tests results, the specimens' mass loss, surface roughness and hardness (before and after tests) were analyzed. All these values were related to the chemical and metallurgical aspect of the samples. It was observed that up to 120 hours of testing, the white cast iron had a lower weight loss when compared with the other materials. From 144h, an inversion of performance took place with one of the ductile irons, which showed the lowest wear rate until the end of test, at 196h. The result is credited to the presence of retained austenite in the ductile iron. This fact provides abrasion resistance due to subsequent transformation induced by deformation.*

Keywords*: Cast Iron, Wear Resistance, Austempering*

1. INTRODUCTION

Cast irons are widely used in industry, mainly because of the ease of filling intricate molds and low fabrication costs. However, the main problems in their use have always been related to low ductility and low toughness compared with steel. In this gap austempered ductile irons (ADIs) are presented. This material has the usual advantages of cast iron, as cast ability, and also with excellent values of strength and toughness. The ductile cast irons are alloys of Fe-C-Si, which, by virtue of its particular microstructure, have mechanical properties similar to those present in some steels. As the graphite nodules are spherical, they don't act as stress concentrators as in gray cast iron. This fact allows obtaining materials with better mechanical strength and ductility. Comparing with the traditional ductile iron, ADIs permit, to the same level of ductility, more than double the tensile strength. Also improvements in the properties of wear resistance and fatigue are widely reported in the literature (Hafiz, 2003). However, in certain parts working in active contact with abrasive elements, we must combine in the same material good impact strength and wear resistance. This task requires considerable attention, since they are qualities that the addition of one is obtained, usually at the expense of another (Shibutani et al, 1999).

In general, the higher is the hardness, the greater the wear resistance, although there is a simple and direct correlation between the two properties (RavishanKar et al, 2008). In applications with high wear resistance requirements, the use of materials with high hardness is normal, provided that no requests of impact resistance are present (Santos, 1989). Currently, in applications with severe abrasion and erosion characteristics, white cast irons with high chromium have been widely used with relative success. These materials are used in equipment such as grinders for ores, gravel and cements, and also in parts of pumps for processing hard materials. Its exceptional abrasion and erosion resistance is mainly a result of its high content of hard carbides, which can be increased by the addition of other alloying elements and heat treatments appropriate (Adler and Dogan, 1999). Usually, whenever a component needs high wear resistance, the option is the use of white cast iron with high amount of alloying elements. This can be not a good option, because this material is very fragile and with high manufacturing costs. In the technical literature are extensive mentioned excellent results of the wear resistance for ADIs (Galarraga and Tschiptschin, 2000).

2. MATERIALS

In this study, three different types of cast iron were employed. They were characterized in terms of hardness and metallurgical structure. After, they were subjected to comparative tests of abrasive wear resistance. The materials used in this study were a quenched and tempered ductile cast iron (QTDI), an austempered ductile cast iron (ADI) and a white cast iron (WCI). In the ADI, two different austempering temperatures were employed, thus obtaining four different samples for the wear tests. Regarding the chemical composition of the samples, the only difference between the batch for austempering and batch for normal quenching was the addition of 0.4% of molybdenum in the first one. Molybdenum is well known as a hardening agent, as well as an increaser in the samples hardenability (Martinez, 2010).

Table 1 shows the chemical composition of studied materials.

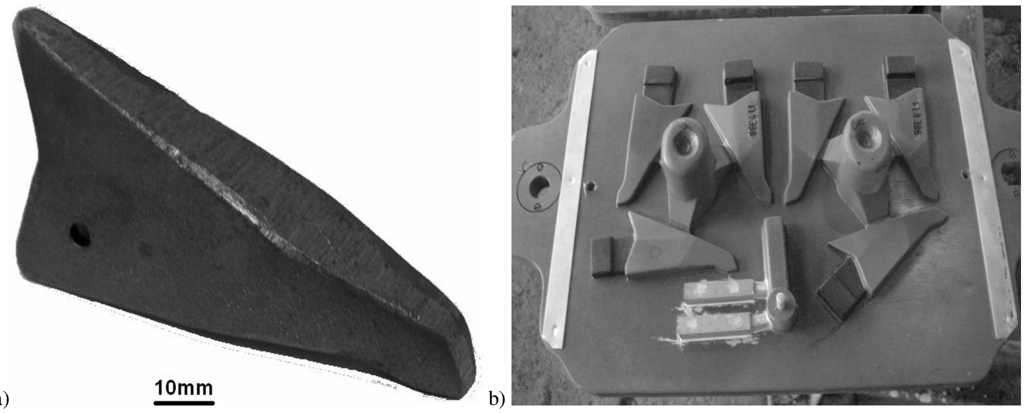
Table 1 - Chemical composition of the studied materials (wt%).

	C	Si	Mo	Cr	Ni	Mn	Mg	P	S
QTDI	*3,81*	*2,30*	*0,08*	-	-	*0,21*	*0,04*	*0,05*	*0,01*
ADIs	*3,72*	*2,39*	*0,42*	-	-	*0,21*	*0,04*	*0,05*	*0,01*
WCI	*2,99*	*1,18*	*1,12*	*18,51*	*0,91*	*0,83*	*0,04*	*0,05*	*0,035*

3. METHODS

The batches for both ductile irons were obtained in an induction furnace, with 92% pig iron and 8% of steel scrap. The nodularization treatment was performed in the pan with the addition of FeSiMg and the inoculation treatment was performed on the liquid metal jet, with the addition of FeSi (Cardoso et al, 2010). The melting temperature was 1540°C and the molds were made of green sand with mechanized molding. To the ADI samples the heat treatment sequence was as follows: preheating to 450°C for about 2h, austenitizing at 900°C for 2 h and austempering in salt bath at temperatures of 260 and 300°C for 2 hours. To the quenched ductile iron samples the sequence was as follows: preheating to 450ºC for 2h; austenitizing at 900ºC for 2 h in salt bath and quenching and tempering for 2 hours at 200ºC in salt bath. To the white cast iron samples, the molding process was performed with cold cure sand (phenolic resin). The specimens were quenched in air, with austenitizing temperature of 900°C and tempering at 480°C.

To the wear tests, four pieces with the same format were produced, one for each class of material. The geometry shown in figure 1 was chosen by virtue of having a format akin to that used in machines for tillage. Figure 1 also shows the plate model used to obtain the mold.



a) b)

Figure 1 - Aspects of the wear test: a) format of the wear specimen and b) plate model for molding.

Figure 2 shows an overview of the test equipment. The equipment consists of a vertical axis in which, at fixed spacing's, in order to ensure a uniform pressure of abrasive in all the samples, are fixed the specimens. After, the axis with the samples set was encapsulated by the frame of the equipment and the abrasive element was deposited on the samples, leaving the shaft assembly/test specimens immersed in the abrasive.

The shaft speed was 360 rpm, which resulted in a peripheral speed of the outside parts of approximately 4.9 m/s. The test was conducted according to ASTM G65-00, monitoring weight loss over the testing time. The initial mixing of the abrasive element was composed of 50% sand and 50% gravel. In each cycle of 24 hours, all spent abrasive (final mixture) was removed, the samples were weighed and then new mix of the abrasive element was added. The specimens were jet washed in hot water with high pressure to remove fouling and then dried and weighed in digital equipment with resolution of 0.5g. In relation to the abrasive, the fineness modulus (ASTM G65-00) of the sand was measured as 2.7 and the maximum size of the abrasive, in mm, as 2.4. For gravel, the measured values were 4.5 and 6.3, respectively. Thus the fineness modulus of the initial mixture of abrasive was 3.6 and the maximum size of the abrasive of 4.3 mm. For the final mixture (after 24 hours of testing), the fineness modulus was measured as 3.3 and the maximum size of the abrasive of 4.1, demonstrating that there was no significant loss of effectiveness of the abrasive element throughout the test.

a)  b) 

Figure 2-Aspects of the wear test: a) overall view of the equipment and b) arrangement of the pieces in the test.

Besides the evaluation of weight loss versus time of testing, the surface roughness is a parameter that can assist in determining the performance of a material against the request of wear. The roughness was evaluated in the position shown in Figure 3, with roughness Ra and cut-off of 2.5 mm. The ranges for measuring surface roughness were not the same as those used in the measurements of mass loss. In the same region of the final measurement of the roughness, the samples were analyzed via scanning electron microscopy to verify their surface appearance.

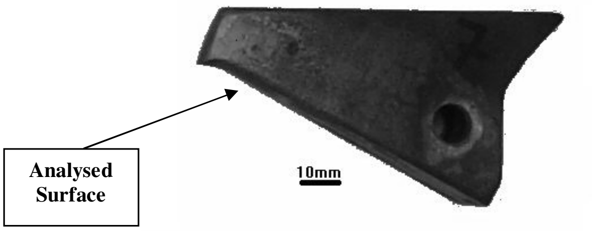


Figure 3 - Position of the assessment of surface roughness.

4. RESULTS AND DISCUSSION

In terms of microstructures, the quenched cast iron consisted of nodular graphite dispersed in a matrix of tempered martensite. The two austempered cast irons consisted of nodular graphite dispersed in a matrix of ausferrite, composed of retained austenite and acicular ferrite (Nofal and Jekova, 2009). Regarding the batches that originated these materials, it can be seen that the processes of inoculation and nodularisation were equal to both materials. Thus it is not expected big difference in terms of quantity, size and degree of graphite nodularisation. It is known, however, that molybdenum reduces the efficiency of inoculation, which could lead to differences in the population of graphite for the two types of ductile iron studied. Still, this difference has a greater influence on properties of impact resistance and tensile strength (which is not the scope of this paper) than in the properties of wear resistance (Cardoso et al, 2010). It is mentioned that all samples possessed graphite size of 6-8 and nodularisation degree above 90% (ASTM A247). Moreover, the thermal treatment employed have a strong influence on the percentage of retained austenite found in the samples, which, according to the literature (Cardoso et al., 2010), has an important influence on wear resistance by the transformation of austenite into martensite induced by deformation. The values of retained austenite were found as of 21% for ductile iron austempered at 300^0C, 12% for ductile iron austempered at 260^0C and less than 5% for the quenched nodular cast iron. These values were obtained by image analysis with the use of software "Image Tool." The white cast iron consisted of chromium carbides dispersed in a martensitic matrix.

Figure 4 shows representative micrographs of the samples. Because of the microstructural constituents of both austempered cast irons are the same, with changes only in the amount of retained austenite, it is shown only one illustrative figure of these materials (fig. 4b).

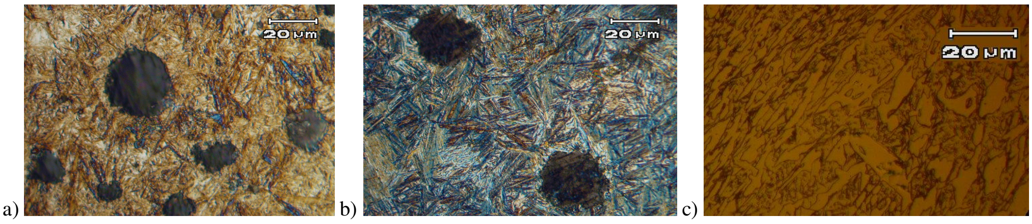


Figure 4 - Metallographic representation of the samples: a) QTDI, b) ADI 300^0C and c) WCI.

Table 2 presents the hardness values of the samples after their thermal treatments.

Table 2 - Values of samples hardness after heat treatment (s - standard deviation).

	ADI 260ºC		ADI 300ºC		QTDI		WCI	
	Mean	**S**	**Mean**	**S**	**Mean**	**S**	**Mean**	**S**
Hardness HB	**414**	**7,0**	**397**	**4,0**	**549**	**5,0**	**544**	**43**

It can be seen in table 2 that the ADI 260^0C showed greater hardness than the ADI 300^0C because its austempering temperature is lower. The hardness values of the quenched ductile iron and the white cast iron are quite similar.

Table 3 presents the results of wear resistance test to the studied materials, presented in terms of accumulated mass loss during the test.

Table 3 - Values of accumulated mass loss of the studied materials.

Time (h)	**Accumulated mass loss (g)**			
	QTDI	**ADI 260ºC**	**ADI 300ºC**	**WCI**
24	**2**	**2**	**2**	**1**
48	**7**	**10**	**5**	**4**
72	**11**	**14**	**10**	**7**
96	**19**	**24**	**16**	**12**
120	**28**	**33**	**23**	**18**
144	**35**	**37**	**28**	**28**
168	**42**	**42**	**35**	**37**
192	**51**	**50**	**37**	**41**

Figure 5 presents the graphical representation of the values from table 3.

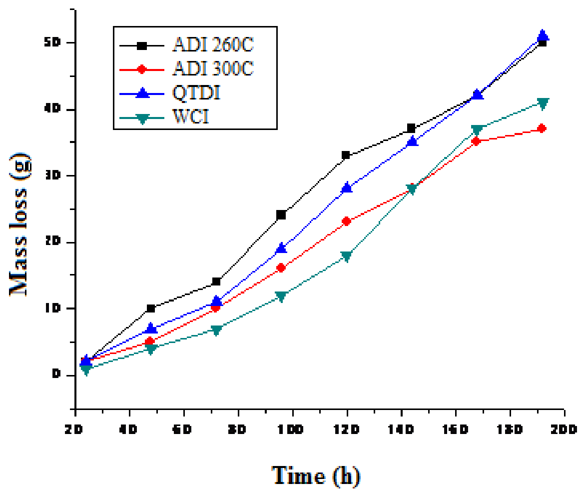


Figure 5 – Accumulated mass loss of the samples.

Analyzing the results in table 3 and figure 5, the WCI showed higher wear resistance since the start of the test, followed by ADI 300^{0}C, QTDI and ADI260^{0}C, respectively. Besides the high hardness, the WCI has hard carbides, which increases its resistance to wear. If the wear resistance analysis were made only in terms of hardness, without taking into account other factors influencing in the tribological system, the order of wear resistance should be QTDI, WCI, ADI 260^{0}C and ADI 300^{0}C, respectively (table 2). However, figure 5 illustrates that for a test time up to 140h, the sequence of higher wear resistance is WCI, ADI 300^{0}C, QTDI and ADI 260^{0}C, respectively. Before the wear test, the ADI 3000C is the material with the lower hardness. Nevertheless this material has the higher retained austenite content (21%), and during the wear test there is a transformation of retained austenite into martensite induced by deformation (Hanc and Binczyk, 2008). It is believed that this transformation begins in the first hours of testing, as since the beginning of the test ADI 300^{0}C (397 HB) has higher wear resistance compared to QTDI (549 HB). Regarding ADI 260^{0}C, its amount of retained austenite is lower (12%), and was not enough to cause minor mass loss than QTDI.

It was observed an inversion in the wear resistance mechanics and for WCI and ADI 300^{0}C over 140 hours of testing. It is mentioned that the transformation of retained austenite into martensite induced by deformation is superficial, since the specimen in the test is only submitted to mechanical efforts in the outer surface. The austempering is an isothermal treatment, thus it gives the same structure throughout the whole piece (Francucci et al, 2008). By this way, even after high test times and considerable wear in the samples, there will always be the same percentage of retained austenite ready to transform into martensite.

On the other hand, the WCI and the QTDI were exposed to continuous cooling treatment. Thus it is expected that there is a gradient of heat extraction during their thermal treatment, with the inner parts of the samples presenting lower wear resistance.

Such assumptions are in accordance with that observed by Haseeb et al, 2000, that, in wear resistance studies for ADIs and QTDIs with similar hardness, noted that the main factor influencing in the wear resistance of is the tribological system in which they are requested, and not only their hardness.

The measures of surface roughness Ra are shown in figure 6. It is noted that the measurements were not made in the same time intervals of the mass loss measures to prevent long test times.

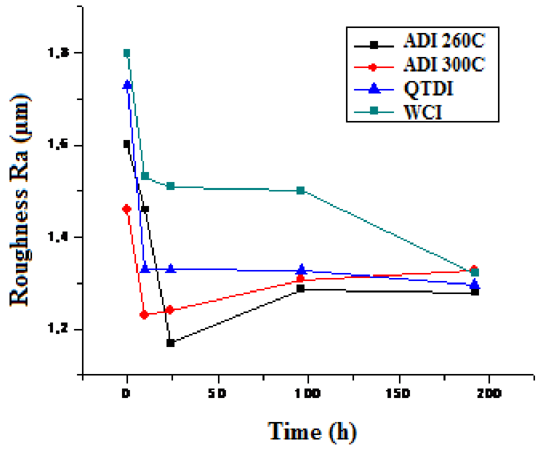


Figure 6 - Comparison of the roughness Ra of the samples tested.

In general there was a reduction of roughness with increasing test time. The trend in a wear abrasive test is that the materials show the abrasive profile in the end of the test. After the first hour of testing, there was a sudden drop of roughness, which can be explained by the fact that the samples were in as cast structure before undergoing the test, which is broken down quickly in the presence of abrasive.

Analyzing individually the different materials, one can see that the ADIs (in both conditions evaluated) showed considerable decrease in roughness in the begin of the test. It is related to its hardness, lower than the other two materials (table 2). After 100h there was an increase in roughness of ADIs, remaining almost stable until the end of the test. The sharp fall and subsequent rise in the value of roughness is justified by a possible plastic deformation of the softer materials (austempered), giving the appearance of low roughness. In the course of the essay the abrasive wear acts, raising the roughness values of these materials. To the QTDI, in function of high hardness, plastic deformation neither was nor verified, and its roughness value quickly stabilized. The white cast iron, due to its high hardness and presence of carbides, after reducing the initial roughness, remained constant until about 100 h and subsequently present a considerable drop. Close to this time, the material showed a reduction in resistance to wear. At the end of the wear test, there was very little variation in roughness between the samples.

Figure 7 shows the surface appearance of samples (196h). We can observe the extension of some linear grooves, which probably should have been triggered by a single abrasive each risk. These risks are only observed in the ductile iron samples.

For samples of ADI260 and ADI300ºC (Figure 7a and 7b), the particles presented can be related to the onset of oxidation of the sample. For both, the aspect is quite similar, but in the ADI260ºC, the risks are more widely spaced and deep than in ADI300ºC. It is observed that the sample QTDI (Figure 7c) shows high surface irregularity, as was the one with the lowest wear resistance.

The white cast iron (Figure 7d) showed little surface deformation, with some non-linear risks. This can be explained by the possibility of hard particles of material breaks during the test. These particles can act as a third body in the abrasive wear test.

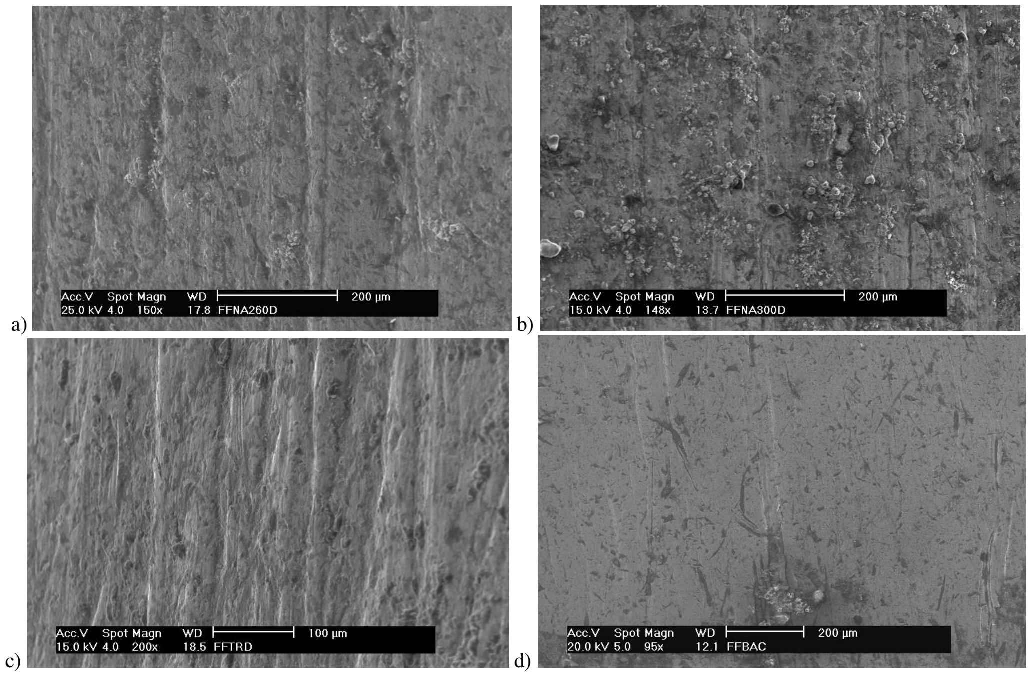


Figure 7 - Appearance of surface samples: a) ADI 260^0C, b) ADI 300^0C, c) QTDI and d) WCI.

5. CONCLUSIONS

Austempering temperature determines the amount of retained austenite. Larger amounts of retained austenite must be processed with higher austempering temperatures (for the same austenitizing temperature).

The wear resistance is not proportional to the material hardness, it is believed that the main factor is the tribological system applied to the material.

Beside the fact that the materials present significant differences in hardness and wear performance, the surface roughness was similar among the four casts evaluated.

In the worn surfaces of the four cast irons studied, their surfaces show scratches, indicating that abrasive wear occurred at low pressures.

In the test of wear resistance, as expected, it was observed that the white cast iron has good resistance characteristic. The ADI300^0C presented during the test little difference compared to the white cast iron. For long exposure times to the abrasive material, the ADI 300^0C showed lower weight loss due to the constant transformation of retained austenite into martensite induced by deformation.

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