EFFECT OF INITIAL SURFACE ROUGHNESS ON WEAR MECHANISMS OF CONTACT FATIGUE – TESTS WITH AUSTEMPERED DUCTILE IRON

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Abstract. *Austempered ductile iron has been tested as a wear resistance material for many applications where the applied loads are very high and cyclic, as gears. This work analyzed the mechanisms of failure of this material in a wear testing equipment projected and build to simulate contact fatigue stresses in a lubricated ball-on-flat system. All tests were performed at 1.2 GPa of maximum Hertz pressure, using ISO 46 lubricant at 50 ºC, until 10^6 cycles. The effect of initial surface roughness was studied for two conditions: grounded and polished specimens. The worn surfaces were characterized by means of optical microscope and by the difference between unworn and worn surface profiles. It was found that the surface roughness affects two damage mechanisms: the plastic deformation of asperities and the removal of graphite nodules. For grounded specimen, the plastic deformation of asperities was more intense and the removal of the graphite nodules was less pronunciated that observed for the polished specimen. Even that, the widht and the depth of the wear track were higher after wear tests for grounded specimen. Also, it was observed for the polished specimen that the contact of stylus profile with the graphite nodules can be affected the roughness results.*

Keywords: *contact fatigue, austempered ductile iron, surface roughness*.

1. Introduction

A mechanical system is usually made by elements that work in contact and under loading. The result of this contact after certain period of time is the wear, characterized by the material removal from surface. A particular mode of wear is those caused by contact fatigue, which occurs in components subjected to cyclic pressures, as gears and rolling, an this mode of wear is the main cause of fail in these kind of components (ASM Handbook, 1992).

During the project step for these components, it is aimed conditions to reduce the severity of operational conditions. A usual solution is the use of lubricant, which can be able to produce a layer among the surfaces and it should have a low shearing resistance. In some lubricated systems, the lubricant separates completely the surfaces and the junctions among asperities are not be generate, resulting in a reduction of wear rate (Hutchings, 1992).

Another way to reduce the contact fatigue wear is the appropriated materials selection. Usually, ultra cleaned and hardened steel are employed. Nowadays, components as gears have been made using steel with high level of alloy elements, following with heat treatment. Another possibility is the use of cast irons (especially the austempered ductile iron – ADI), although there is the stress concentration created by graphite, they have showed a satisfactory performance when subjected to contact fatigue wear (Fuller, 1985).

The amount of wear can be determined by means of laboratorial tests, which simulated the conditions of loading, velocity, temperature and lubrication. This step is very important to verify the success of the selected way to reduce wear, either the modification of operational variables or the materials selection. Equipments have been developed to study the wear mechanisms of contact fatigue. Their main characteristics are the non-conformity of the geometry (e. g. ball-on-flat and disc-on-disc), the possibility of huge contact pressures and the different lubrication regimes (Hutchings, 1992).

The aim of this paper is to analyze the wear mechanisms of contact fatigue in experimental conditions, using the austempered ductile iron as the material in different conditions of the initial surface roughness (grounded e polished).

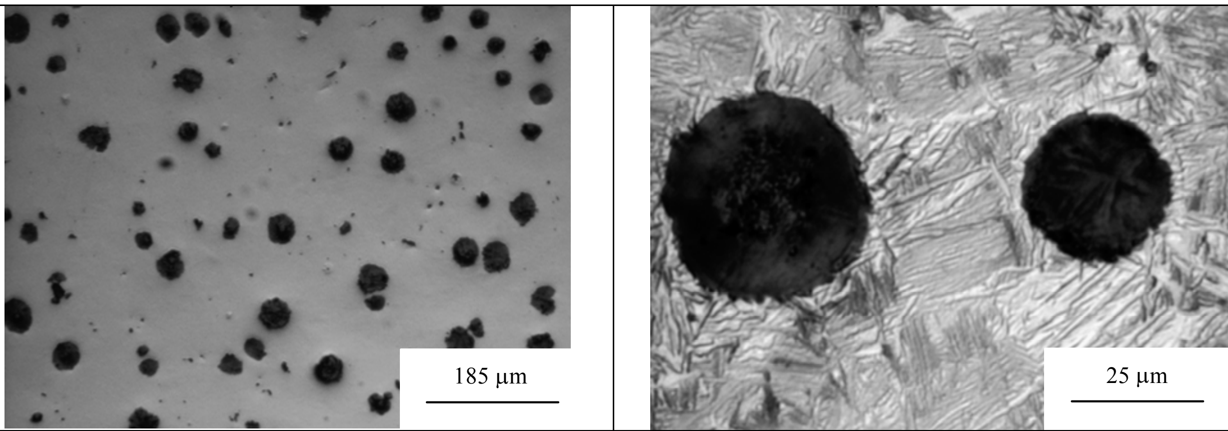
2. Materials and methods

The specimens were produced from bars of ductile iron (diameter = 95.3 mm / thickness = 45 mm), made by FUNDIÇÃO TUPY S/A through continuous casting. Table 1 presents the chemical composition of the tested material.

Table 1. Chemical composition of nodular cast iron (mass %).

C	Si	Mn	P	S	Cr	Cu	Mo	Mg
3.71	2.54	0.18	0.065	0.01	0.031	0.72	0.186	0.038

The bars were austenitized at 910 ºC by 1.5 h and austempered in bath salt, at 290 ºC by 2 h, following air-cooling. Figure 1 presents the metallurgical characteristics of the austempered ductile iron in the as-received condition.

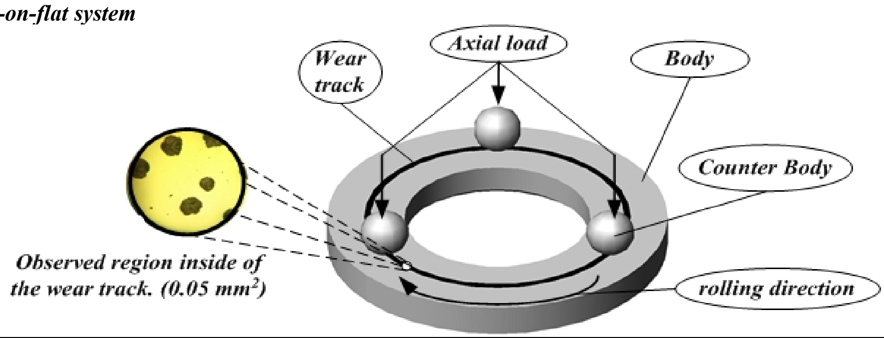


a) Form and distribution of graphite nodules. % of nodules = 10 ± 0,6 % Average size of nodules = 23 ± 10 μm Brinell hardness HB 2.5/187.5 = 362 ± 12	b) Metallic matrix: inferior bainite Vickers hardness of matrix HV 0.05 = 508 ± 28

Figure 1. Metallurgical characteristics of ADI in as-received condition.

The bars were turned, producing specimens with ring geometry (see Fig. 2) and further they were grounded. The wear tests were performed in ball-on-flat equipment, projected and building in the Contact and Surfaces Lab – LASC (Leite *et al.*, 2005). Figure 2 presents the specimen dimensions, the counter-body dimensions and the experimental conditions of tests.

Ball-on-flat system



Body		***Counter Body***	
material	Austempered Ductile Iron	material	AISI 52100
dimensions (mm)		dimensions (mm)	
dia ext	55	diameter of the sphere	7.9375
dia int	30		
largura	5.5		
surface roughness	grounded and polished	roughness (Ra - μm)	0.01
Interfacial Conditions		***Tests Conditions***	
lubricant oil	ISO 46 (1)	maximum Hertz pressure (GPa	1.2
oil temperature (ºC)	50	speed (rpm)	1700
oil volume (l)	1.2	contact points	3
type of lubrification	circulation	load cycles	10^6

(1) oil IPITUR AW 46, of the IPIRANGA manufacturer.

Figure 2. Specimens dimensions and experimental conditions.

It was studied two condition of initial surface roughness, called *polished* and *grounded*. The polished surface was prepared using diamond grains of 1 μm and the grounded surface was obtained using aluminum oxide paper #220 (average grain size of 66 μm).

The analysis of the worn surfaces was made by means of optical microscopy and roughness profiles.

The removal of graphite nodules was estimated by metallographic counting in the following regions, all corresponded to areas of 0.05 mm^2 (see Fig. 2):

- Wear track of polished specimen;
- Outside of wear track of polished specimen (similar to initial counting, as showed in Fig.1);
- Wear track of grounded specimen and;
- Outside of wear track of grounded surface.

In each counting, it was identified the empty nodules, generated by the removal of the graphite.

The roughness measurements were performed in TALYSURF SERIES 2 equipment. The evaluation length was 4 mm. The worn surface was disposed to the perpendicular direction to the stylus diamond and the measurement was started in a point outside of the wear track. The profiles were treated in the TALY PROFILE software – 3.1.10 version. The routine of treatment was made using a filter, a polynomial equation, in order to became the profile parallel to the horizontal axis. In the adjusted profile, the wear track was determined, its depth and width, in two different regions.

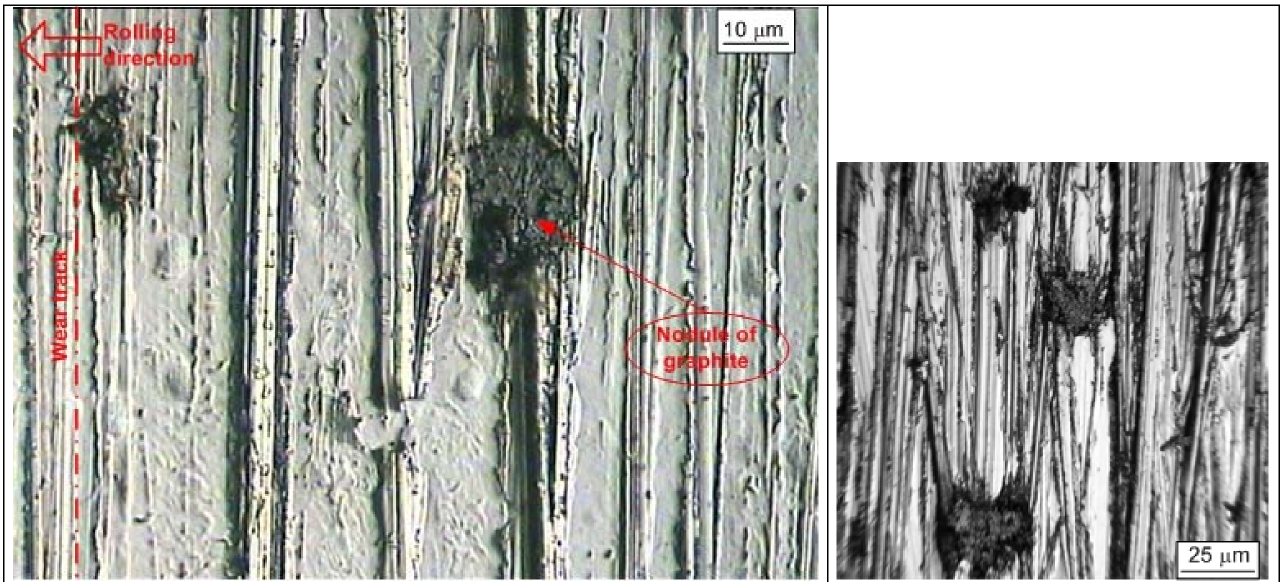
3. Results and discussion

The effect of initial roughness on the wear mechanisms will be related to: i/ the deformation of the wear track and e ii/ the removal of graphite nodules.

3.1. Deformation of wear track

3.1.1 Depth of the wear track

Figure 3 (a) presents a region inside wear track of the grounded specimen and Fig. 3b this specimen before wear test.



a) b)

Figure 3. Optical images of grounded specimen: a) inside the wear track and b) outside the wear track.

In Fig. 3a one can observe that the peaks of asperities, produced during specimen preparation, were deformed, gives rise to areas similar to polished surfaces, and this effect can be checked by the higher light reflection of that the observed in the region outside the wear track (Fig. 3b).

Figure 4 presents the roughness profiles of the grounded specimen for the region inside the wear track (Fig. 4a) and for the outside the wear track (Fig. 4b).

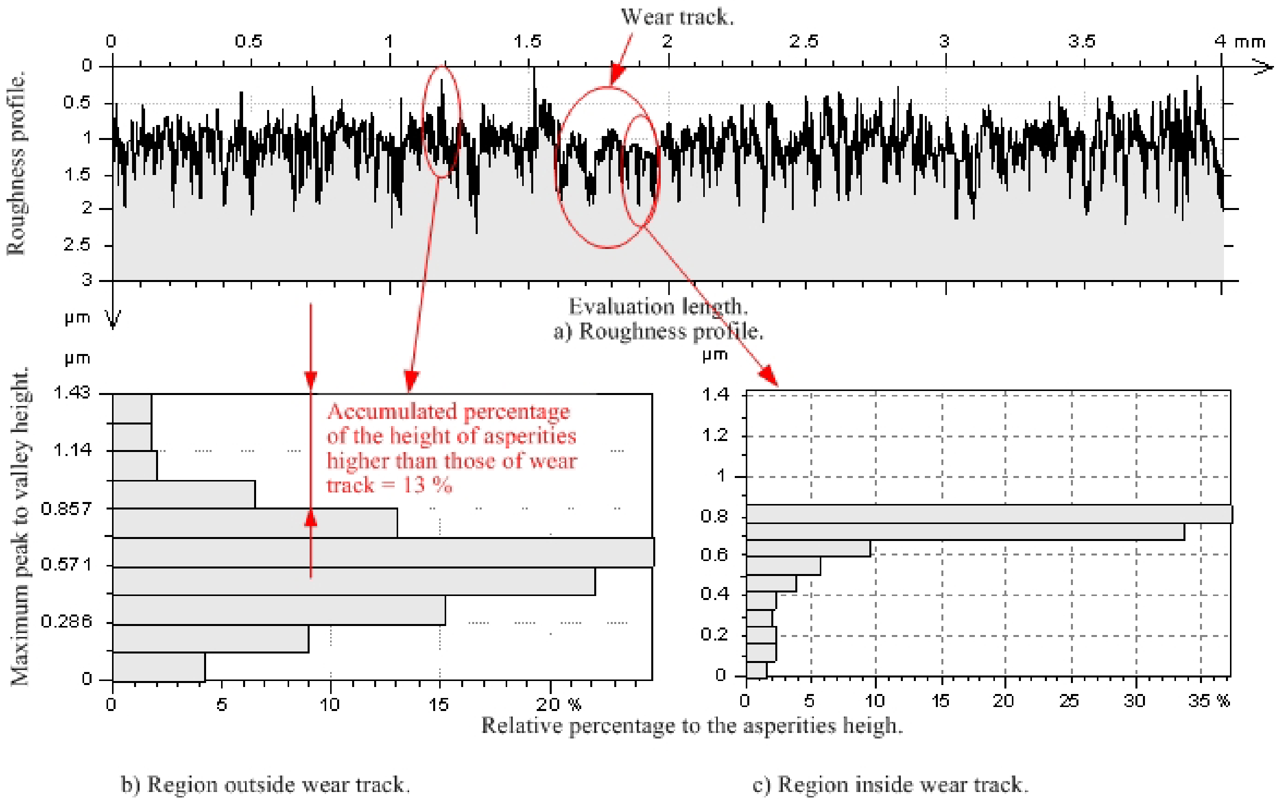


Figure 4. Roughness profile of the grounded specimen.

Figure 4b shows the relative percentage of the height of asperities. Figure 4c shows that the maximum height observed inside the wear track was about 0.8 μm. Considering this value, the region outside the wear track has 13% of asperities higher than this value, showing that occurred a reduction in the height of asperities after wear tests. It can be considered that this reduction was about 0.5 μm in depth.

Figure 5a presents the roughness profiles of the polished specimen for the region inside the wear track (Fig. 5c) and for the outside the wear track (Fig. 5b).

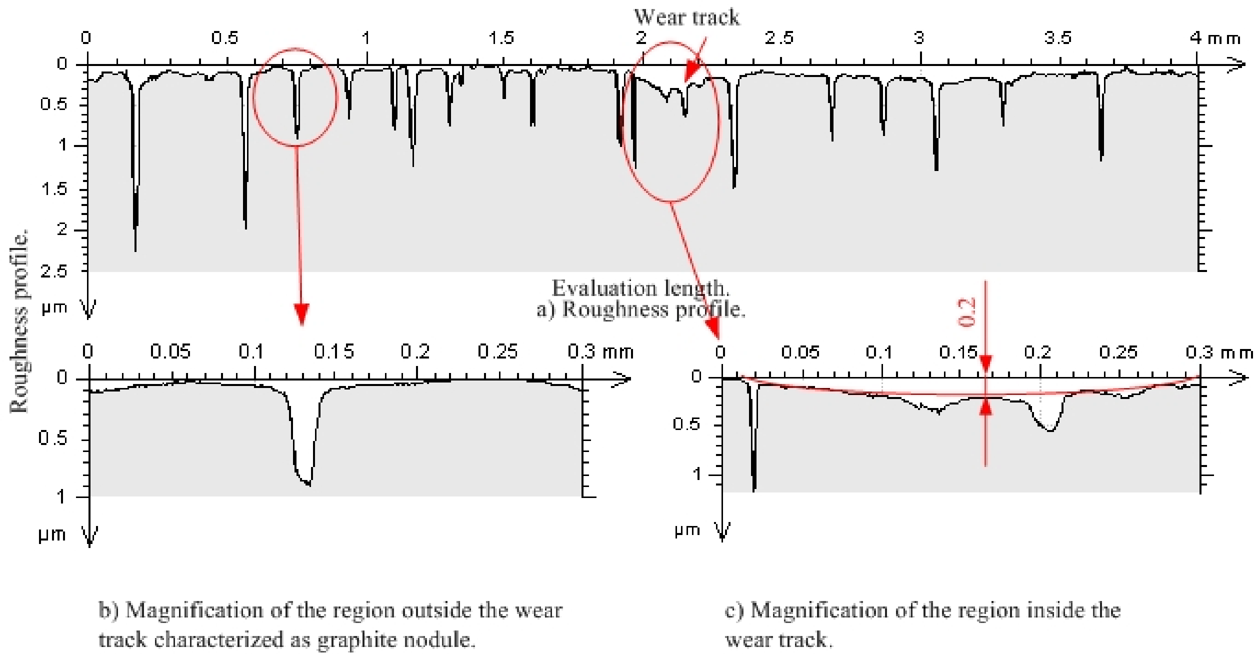


Figure 5. Roughness profile of the polished specimen.

The wear track of the polished specimen could be identified from the roughness profile, and one can observe the depth of 0.2 μm.

Therefore, the depth of the wear track was higher in the grounded specimen. This effect can be explained by the considerations made by Kim and Olver (1998). These researchers verified that the roughness increase the probability of fail, because the stress concentration effect in the rough surface is higher when compared with that calculated using the elastic theory without the effect of the roughness.

3.1.2 Width of the wear track

From the Fig. 4 and Fig. 5 one can calculate the width wear tracks dimensions for each test condition, as presented in Tab. 2.

Table 2. Width of the wear track.

Test condition	*Width [μm]*
polished	214
grounded	346

The increase in the wear track in relation to the calculated considering the elastic contact (≈ 65 μm) has the contribution of two factors:

i/ the radial movement of the ball (counterbody). The ball-on-flat system does not restrict the radial movement of the ball, as occurs in the axial rolling.

ii/ the relationship between surface roughness and lubrication thickness. If the lubrication condition were the same for both tests, surface roughness would increase this relationship. In this case, the expected effect is an increase in the number of metal-metal contacts and, consequently, an increase in the contact fatigue wear, as observed by Phillips and Quinn (1978). The indicative of larger wear rates for these researches was the increase in the width of the wear track, as observed in this paper for the grounded specimen.

3.2. Graphite nodules removal

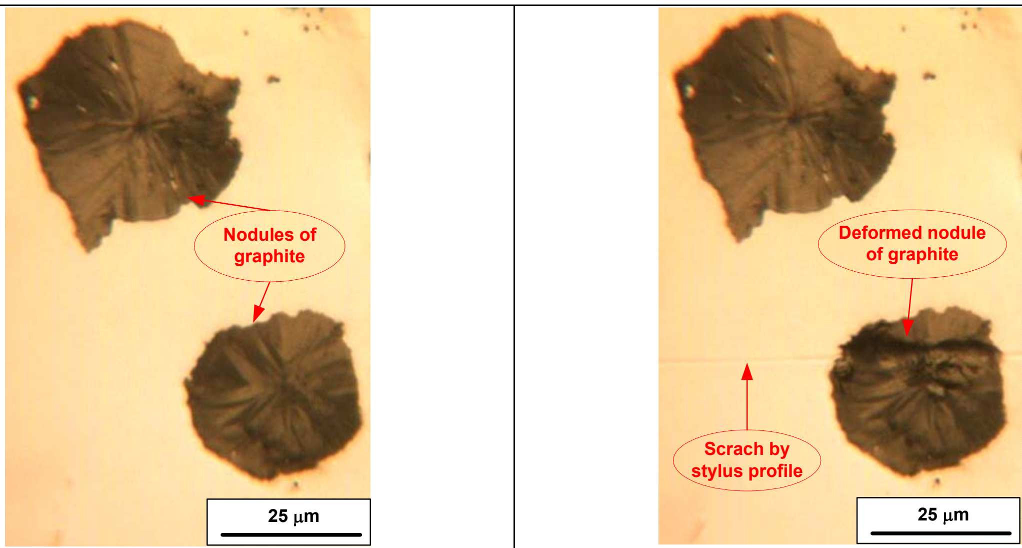
Table 3 presents the amount of empty nodules of graphite before and after the wear tests.

Table 3. Empty nodules of graphite, before and after contact fatigue wear tests.

	% of empty nodules	
Test condition	*before tests*	*after tests*
polished	9	60
grounded	12	39

The results presented in Tab. 3 shows that the wear process was able to remove a large amount of graphite nodules. This effect was higher in the polished specimen. The mechanisms of graphite removal were not easily observed in the grounded specimen, because the plastic deformation of the asperities takes place before the removal of the graphite. For the same reasons, the foundry defects were not observed in the surface of the grounded specimen in the same intensity of that observed in the polished specimen.

A possible variation in the values presented in Tab. 3 is expected, because was identified some singularities in the roughness profiles, outside the wear track of the polished specimen (~24 μm of diameter). These singularities can be associated to graphite nodules (average size of 23 ± 10 μm) removed *during* the roughness measurement. Figure 6 presents two optical images, before and after the contact of the stylus profile.

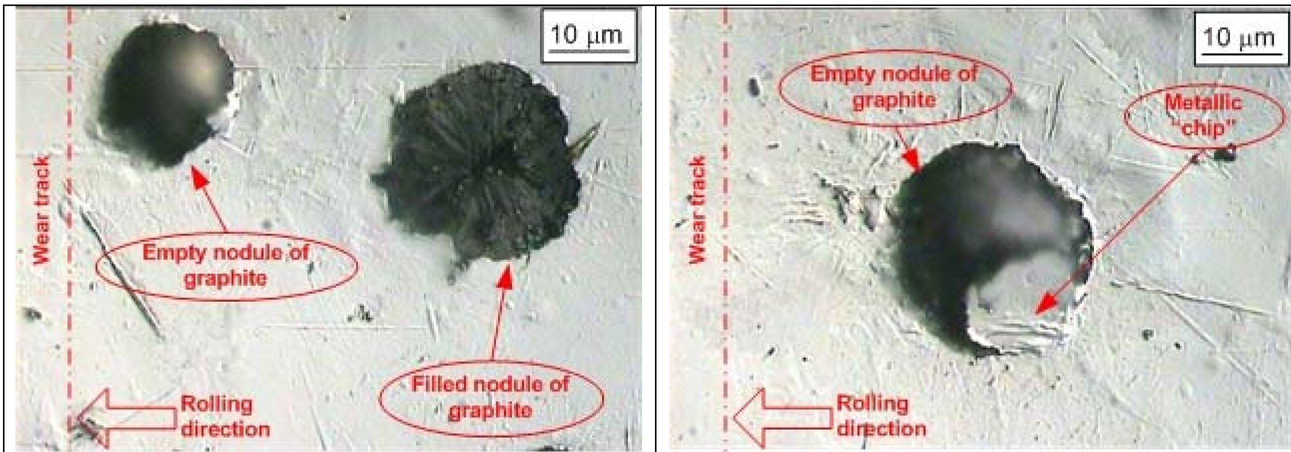


a) Graphite nodules. | b) A graphite nodule after the contact of stylus profile.

Figure 6. Graphite nodules of ADI, before and after the contact with the stylus profile.

The effect presented in Fig. 6 has a large importance for the routines to measure surface roughness of the mechanical components made by cast irons containing graphite, as lamellar, ductile and compacted cast irons. Many of these components are subjected to tribological action, as the cylinder of internal combustion engines (ASM Handbook, 1996), and the surface roughness is an important parameter in the fabrication process of these components (Tomanik, 2000).

The mechanisms of removal of graphite nodules during the contact fatigue wear tests were observed by optical microscopy, as presented in Fig. 7 for the polished specimen.



a) Empty and filled nodule of graphite inside de wear track. | b) Empty nodule of graphite with metallic “chip”.

Figure 7. Empty graphite nodule inside wear track in the polished specimen.

Figure 7 shows the presence of empty nodules of graphite, as well a filled nodule inside wear track. It can be observed in Fig. 7b a kind of metallic “chip”. Following Magalhães, Seabra, and Sá (2000), the mechanisms of graphite removal depend on the position of the graphite in relation to the surface, and this “chip” is broken due the action of the lubricant, which promotes the pull-out of the graphite and consequently, there was no material to sustain the continuity of the deformation in the contact. The present authors studied the effect of the nodules position in the damage mechanisms of contact fatigue and it will be presented in another paper.

4. Conclusions

a) Two damage mechanisms were observed in the austempered ductile iron after the contact fatigue wear tests: the plastic deformation of asperities and the removal of the graphite nodules.

b) The initial surface roughness affects these damage mechanisms in different ways: the removal of graphite nodules was less observed in the grounded specimen, because the plastic deformation of asperities in this specimen was higher than that observed in the polished one.

c) The roughness measurements for the polished specimen were affected by the contact of the stylus diamond, and this kind of result should be studied with more detail.

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