Laser Surface Treatment of a Spheroidal Graphite Cast Steel

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Abstract. *Austempered graphite cast steels are characterized by spheroidal graphite originated from carbide decomposition due to high concentration of carbon and silicon. These steels present better mechanical properties than the austempered ductile iron, less cost of production and higher wear resistance if compared to traditional cast steels. Surface hardening treatments aim to increase the wear resistance of most steels. Laser surface processing of metallic materials has been developed with the aim of improving the properties on the surface of components. This technique has been widely applied in industrial processes due to the unique precision and a very localizes thermal action furnished by the laser high-energy density and power controllability. At higher intensity than that used for hardening, the scanned laser beam can be used to induce melting of a thin layer on metals surface. Inherent to the rapid heating and cooling rate at which this surface layer is submitted, this process provides an opportunity to produce the formation of different microstructures from the bulk metal leading to useful properties. The present work is concerned with the laser surface melting of spheroidal graphite cast steel samples under different processing conditions in order to evaluate the effects of the treatment on the resulting microstructure. The structural characterization of the treated surface was performed by optical microscopy, scanning electron microscopy, X-rays diffraction and Vickers microhardness. The abrasive wear resistance was analyzed by using micro-scale abrasive wear tests.*

Keywords: *spheroidal graphite cast steel, laser treatment, microstructure, wear resistance.*

1. Introduction

Spheroidal graphite cast steels or graphite steels were developed in the sixties. Liked the ductile irons, graphite steels also are submitted to the nodulization process in some moment of the alloy elaboration process (Takahashi *et al.*, 1996). The C and Si contents in graphite steels are lower than those of ductile irons but, in general, are higher than the most of the steels. Due to the high Si and C contents in graphite steels, carbides decompose into free carbon, which is related to the resulting reasonable hardening, good machinability and good wear resistance. Graphite steels are commonly used in bearings, cams, blanking dies, punches, bushings, gages, aluminum deep blanking dies, etc.

Graphite steels are usually submitted to thermal treatments such as quenching and tempering at low temperatures. The typical resulting structures from these treatments are martensite, retained austenite and graphite nodules. The mean hardness (800-1000 HV) varies according to the retained austenite content (Chiaverini, 2002).

Nowadays, some researchers (Takahashi *et al.*, 1996; Putatunda, 2001; Yamamoto and Kobayashi, 2001; Putatunda, 2003; Soufen, 2003) have studied graphite steels in the austempered form, which is aimed to attain new structures with better properties than those of austempered ductile irons. These steels, after the austempering treatment, can present a combination of high yield stress, good ductility, high fatigue resistance, fracture toughness, impact resistance and wear resistance, which is due to the structure of austenite and ferrite of high carbon content (Putatunda, 2001).

The typical matrix of austempered graphite steels is composed of lower bainite and upper bainite, depending on the austempering temperature and austenite of high carbon content. The presence of silicon normally stabilizes the austenite and inhibits the formation of carbides (Sandvik, 1982). The better properties of these steels are also due to the fact that the structure of graphite steels presents graphite in nodule form in less amount and smaller than that in the ductile iron.

The mean hardness of austempered graphite steels (300-600 HV) depends on the austempering temperature because the retained austenite amount increases with the temperature treatment (Soufen, 2003). Higher hardness, due to the low austempering temperatures, is associated with the lower retained austenite, high resistance of the lower bainite, which is the major micro-component of the structure. Other influences which contribute to the high resistance are due to the super-saturation of carbon in the ferrite, that hinders the dislocation movement, increases the dislocation density and distorts the ferrite reticulate (Elliot, 1997; Hamid *et al.*, 1994).

Another possibility to improve the performance of graphite steels, mainly related to the wear and corrosion applications, is the use of laser surface treatments. Due to the laser high power density and the reduced interaction time with the material surface, the rapid heating and cooling rate will induce refined and homogeneous structures or even metastable structures, which can be quite different from that of the bulk metal (Ierardi *et al.*, 1999; Pinto *et al.*, 2003; Cheung *et al.*, 2003; Cheung *et al.*, 2005). The combination of a high surface hardness with the ductile bulk material leads to various applications of graphite steels.

Parallel to the increasing role of surface treatments applied on engineering components in obtaining improve performance, an accelerated development of techniques for evaluating and screening the quality of these surface engineering products has also occurred (Staia *et al.*, 1998). For tribological characterization, traditional techniques such as pin-on-disc or reciprocating sliding wear tests or dry sand rubber wheel test have been used successfully (Satner *et al.*, 1995; Ronkainen *et al.*, 1990) but, particularly for thin hard surface, there can be considerable difficulties in performing tests (Gee *et al.*, 2003) due the very small mass changes associated with removal of a thin surface layer (Hutchings, 1999). A micro-scale abrasive wear test has been developed that allows measurement of the wear resistance of different surface regions of a component. The test uses a simple mechanical and optical system and involves rotating a hard sphere against a specimen in the presence of small abrasive particles. This method has the ability to test small samples, its applicability to specimens with compound curvature at the surface, and the capacity to determine the properties of thin surface layers independently of their thickness and adhesive strength (Rutherford and Hutchings, 1997).

The present work is concerned with the laser surface melting of spheroidal graphite cast steel samples under different processing conditions in order to evaluate the effects of the treatment on the resulting microstructure and the wear resistance. The abrasive wear rate was evaluated by using micro-scale abrasive wear tests and the results were compared with those of spheroidal graphite cast steel austempered samples.

2. Experimental Procedure

Spheroidal graphite cast steel (Fe- 0,9C-1,59Si-0,39Mn-0,45Nb-0,021S-0,019P) was sand cast in a "Y" ingot format according to the ASTM A897-90 standard. Testpieces, measuring approximately 65x12x6mm^3, were machined from this ingot. Their surfaces were blasted with alumina powder to provide a cleaned surface with standard finishing and cleaned prior to the laser treatment.

Surface melting was carried out with a 1kW CW CO_2 laser, from the LNLS (Brazilian Synchrotron Light Source Laboratory), as shown schematically in Fig.1. The samples were moved under the stationary laser beam, using a numerically controlled X-Y table and a laser power of about 159W/mm^2. A range of transverse speeds from 8,3 to 80mm/s was used. In order to permit the treatment of the entire surface, the samples were submitted to multiple scans laser passes, always in the same direction, with overlapped about 50%. Surface oxidation was prevented by flowing argon at the laser beam side keeping a 30° angle between gas flow and with sample surface. Some specimens were austempered, in order to compare to those treated by laser.

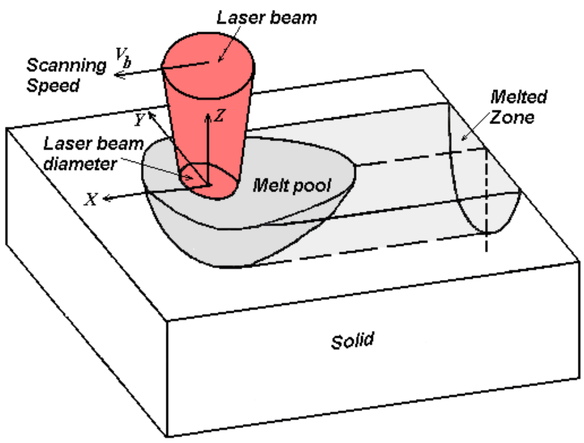

Figure 1: Schematic diagram of laser surface melting process

The microstructural characterization of the laser treated and austempered samples was carried out by optical microscopy (OM), scanning electron microscopy (SEM) and Vickers microhardness measurements under 100gf load on the transverse section of the laser-melted specimens. X-ray diffraction, using Mo Kα radiation, was performed to identify the phases present in the structure.

The abrasive wear tests were performed using a micro-scale abrasive ball-cratering wear test machine, similar to that described by Rutherford and Hutchings (1997). The apparatus is shown schematically in Fig. 2. The ball is driven positively by a shaft. The sample is mounted vertically on the pivoted L-shaped arm and is loaded against the ball by a weight hanging from the horizontal lever. The slurry of 6μm diamond particles in alcohol was fed drop by drop into the contact area. The specification of the apparatus and experimental details are shown in Tab. 1.

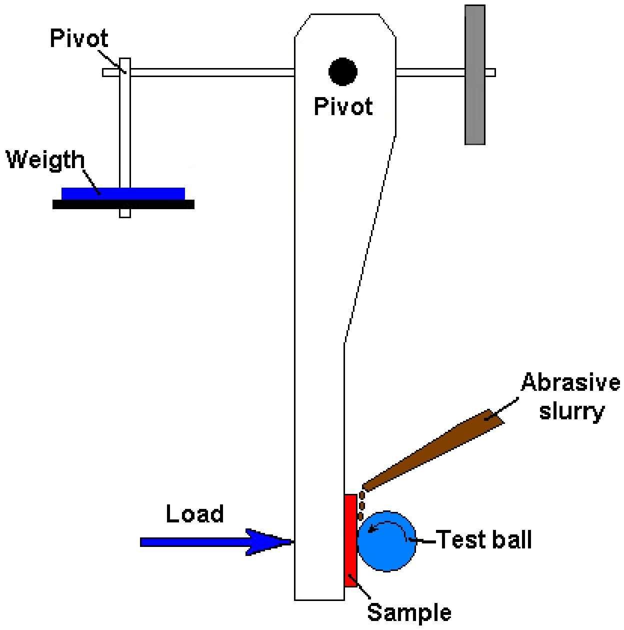

Figure 2: Schematic diagram of the experimental apparatus

Table 1 – Specification of the micro-abrasion apparatus

Load	18,7N
Ball material	AISI 440 stainless steel
Ball diameter	25mm
Ball speed	150rpm
Slurry	6μm diamond particles in alcohol
Slurry concentration	0,2g/cm^3
Slurry feed rate	1 drop/20seconds
Sliding distance	120m

The worn surfaces of the laser melting and austempered samples were observed by scanning electron microscopy. The wear rate was calculated from the measured crater diameter via Eq. (1), where *K* is a wear rate, *b* the crater diameter, *R* the ball radius, *S* the sliding distance and *N* the applied load. The scar diameter *b* was measured by optical microscopy.

$$K=\frac{\pi b^4}{64R}\frac{1}{SN}\,[\text{mm}^3/\text{Nm}] \qquad (1)$$

3. Results and Discussion

3.1. Microstructure

The as-cast structure of the spheroidal graphite cast steel is shown in Fig. 3. The structure consists of a pearlitic matrix with niobium carbides and graphite nodules dispersed in it. The typical structure of the samples austenitized at 900°C and then austempered at 320°C is shown in Fig. 4. The austempered microstructure shows a matrix consisting of a two-phase mixture of bainitic ferrite, which is needle-shaped, and austenite with a few graphite nodules. However, a small amount of martensite can also be observed at the cell boundaries. No precipitation of carbides was detected.

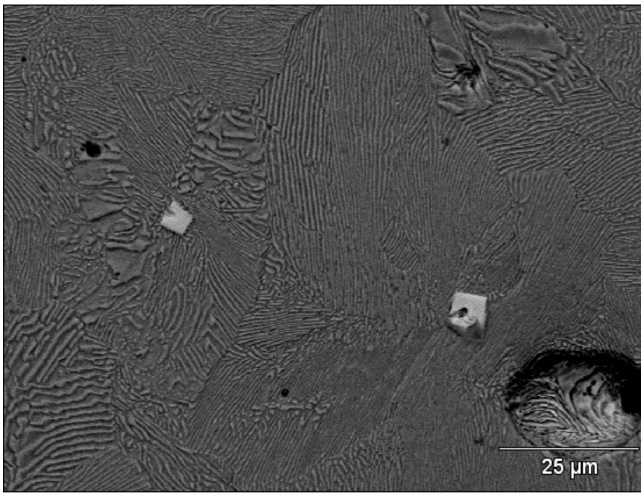

Figure 3: Structure of the as-cast graphite cast steel

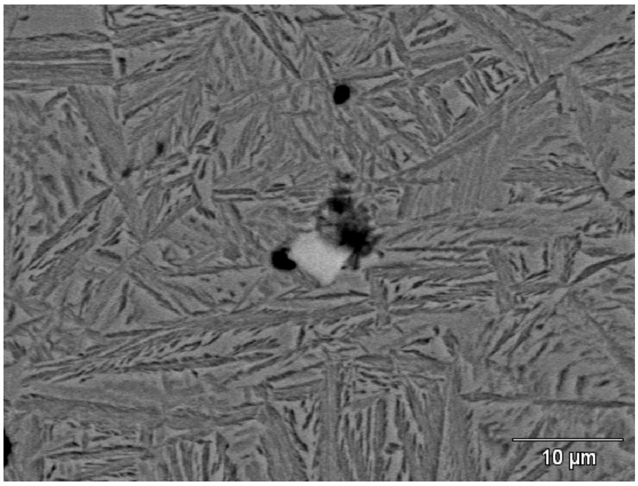

Figure 4: Structure of the austempered graphite cast steel

A typical laser melted structure of the graphite cast steel is shown in Fig. 5. The melted zone presents a very fine structure and is free from defects such as pores and cracks. In this zone, the structure consists of martensite and some retained austenite. A few particles of NbC and graphite nodules were also observed. In the heat-affected zone only solid-state transformations occurred. The microstructure, shown in Fig. 6, consists of martensite, retained austenite and non-transformed pearlite. The presence of retained austenite, even with the high cooling rate imposed by the laser processing, can be explained by both the super saturation of the alloying elements and the highly refined structure that decrease the Ms temperature, promoting the austenite stabilization [Colaço et al., 1999; Colaço and Vilar, 1998; Colaço and Vilar, 1997]. The application of X-ray diffraction has confirmed the metallographic observations.

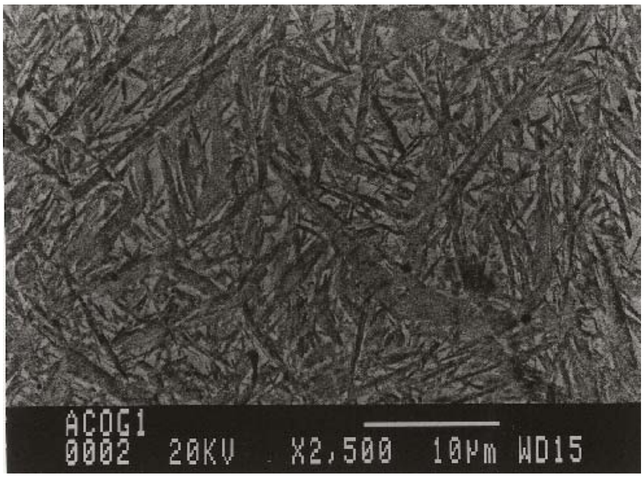

Figure 5: Microstructure of the melted zone

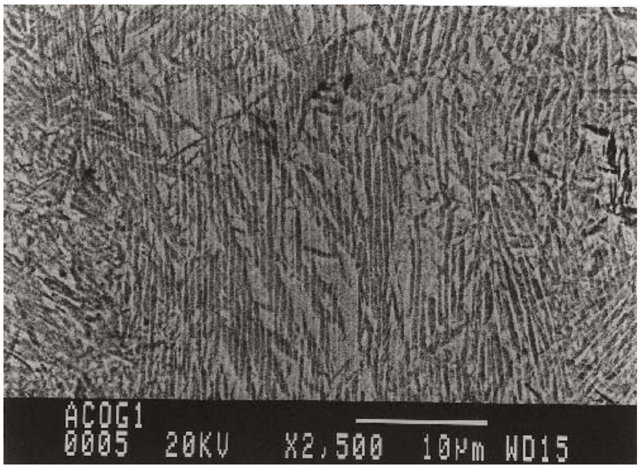

Figure 6: Microstructure of the heat-affected zone near the fusion line

The hardness profile on the transverse cross-section of the laser-melted sample is illustrated in Fig. 7. The hardness of the graphite cast steel after conventional austempering is about 400 HV. The hardness of multiple laser scan treated samples varies between 850 and 1100 HV. Despite the presence of retained austenite, the hardness of the material is remarkably high. This high hardness is explained by the small grain size, high solute content and high dislocation density in austenite due to laser treatment.

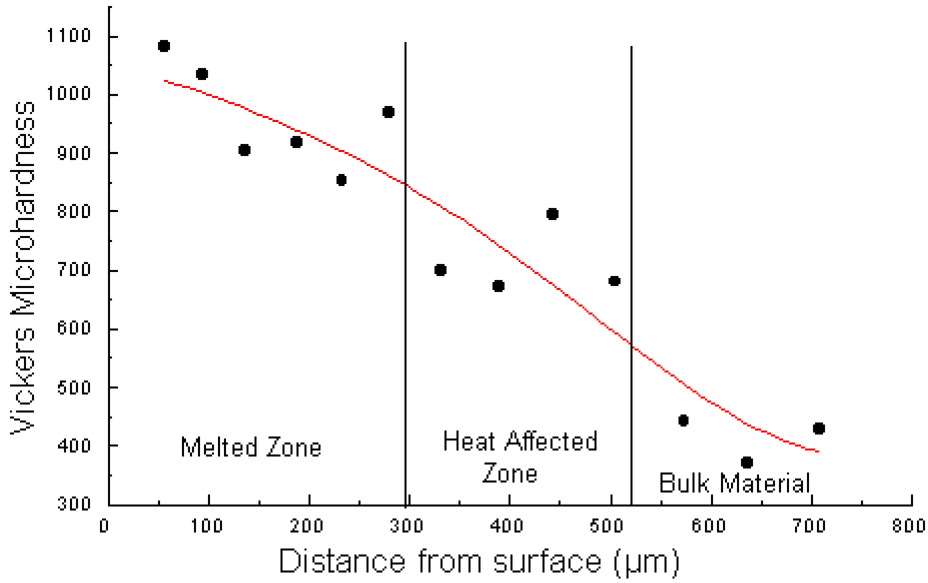

Figure 7: Microhardness profile of a laser melted spheroidal graphite cast steel sample

3.2. Wear Resistance

Figure 8 shows the results of the micro-scale abrasive wear tests. The tests, type sphere-on plate, were carried out on the polished surface of the laser-melted samples. The spheroidal graphite cast steel austempered (SGCS-Austempered) presented the best abrasive wear resistance when compared with the laser melted spheroidal graphite cast steel (SGCS-Laser) and the as-cast spheroidal graphite cast steel (SGCS-As-cast). It was observed that the craters were not well spherically formed, probably due to the high load (18,7N) used in the tests. The high load promotes a mechanism by which slurry did not entrain into the wear contact but instead flows round the sides. The mechanism leads to non-spherical wear crater, characterized by ridge of specimen material in the center of the crater, parallel to the sliding direction.

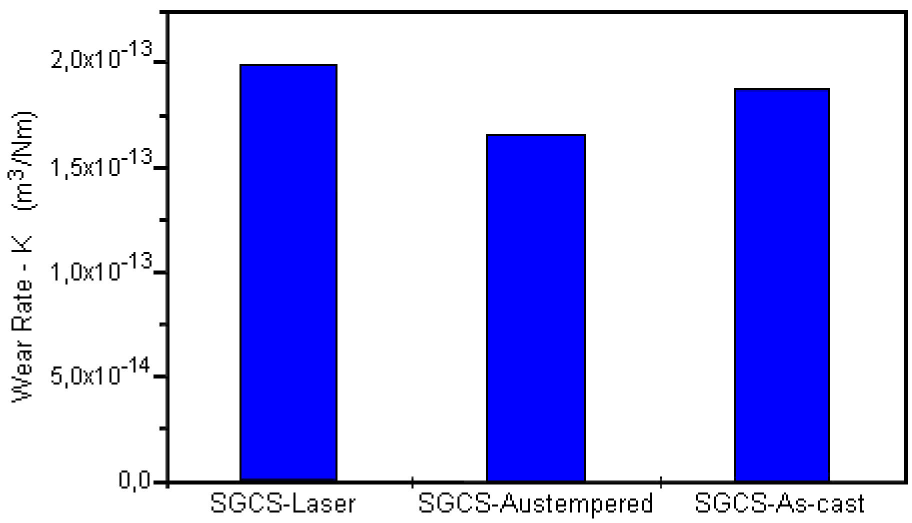

Figure 8: Wear rate of the studied samples

Scanning electron microscopy analysis revealed that the wear craters of the SGCS-Austempered and SGCS-As-cast samples present a series of fine grooves parallel to the sliding direction of abrasive particles and regions heavily deformed (multiply indented wear surfaces with no evidence of surface directionality) originated by the rotation of the abrasive particle between the two surfaces (Fig. 9). This demonstrates that wear predominantly occurs by two mechanisms: micro-cutting and micro-ploughing. Another important observation is the presence of many abrasive particles deeply and firmly embedded in the samples surfaces (Fig. 10), causing the wear of the ball. This fact can explain the lower wear rate exhibited by the SGCS-Austempered and SGCS-As-cast samples in comparison with the wear rate of the SGCS-Laser sample.

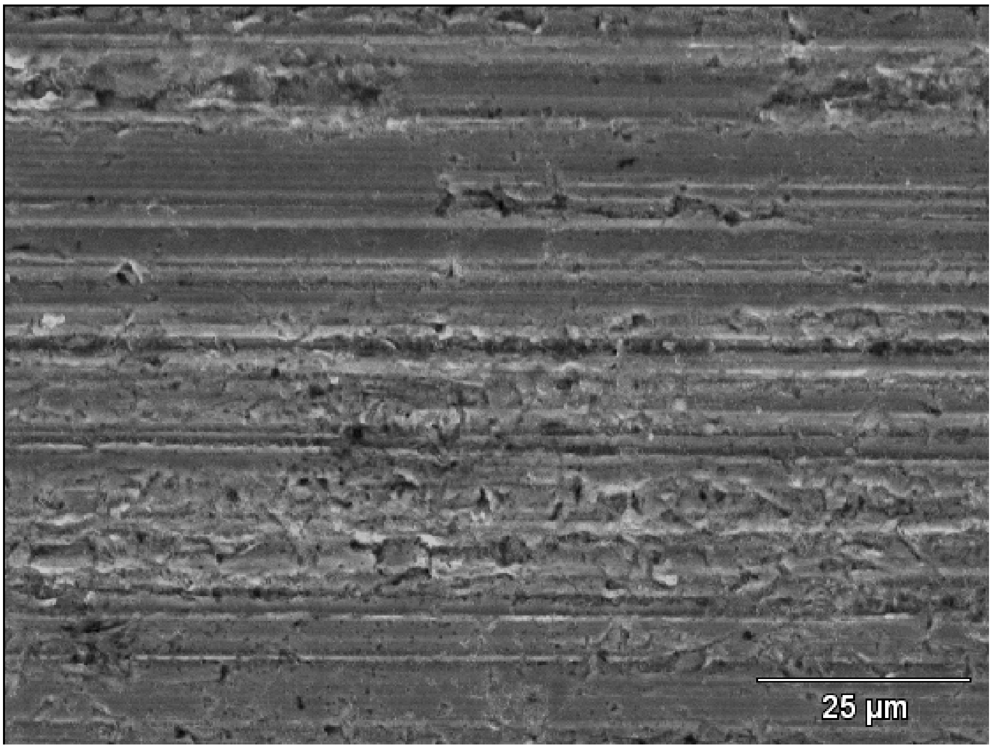

Figure 9: Wear surface of the SGCS-Austempered sample

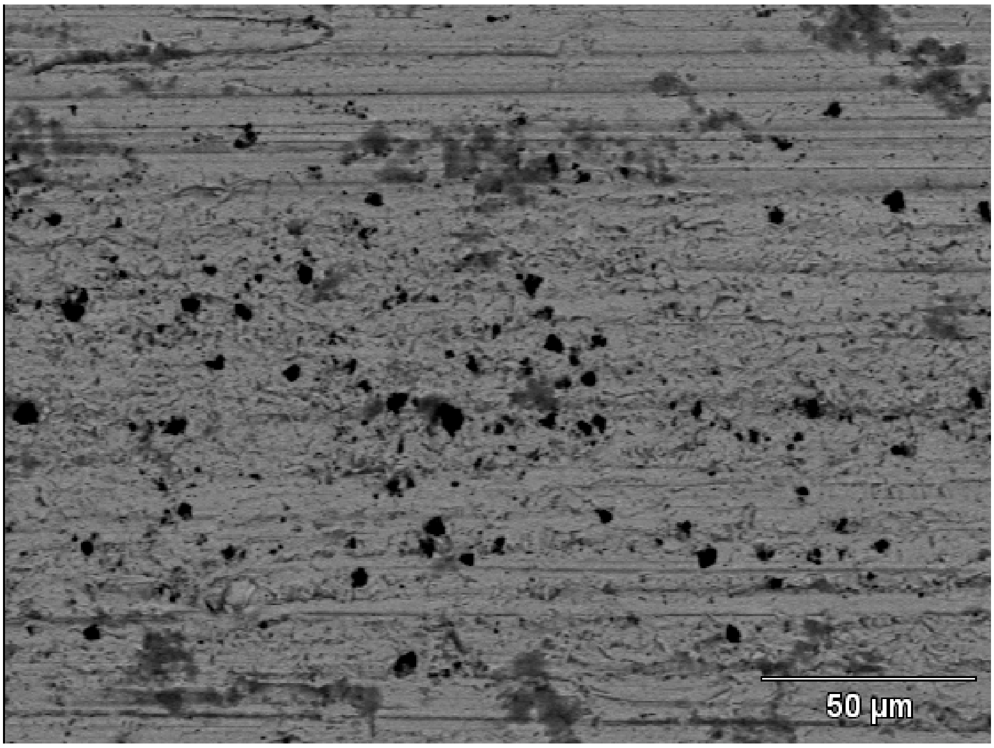

Figure 10: Abrasive particles deeply and firmly embedded in the sample surface

The SGCS-Laser sample presented the wear surface formed only by grooves parallel to the direction of sliding, characteristic of the micro-cutting wear mechanism (Fig. 11). This mechanism is dominant at high loads and/or low slurry concentrations such as those used in this work. The grooves are less deep, steep-sided and formed by the abrasive particles.

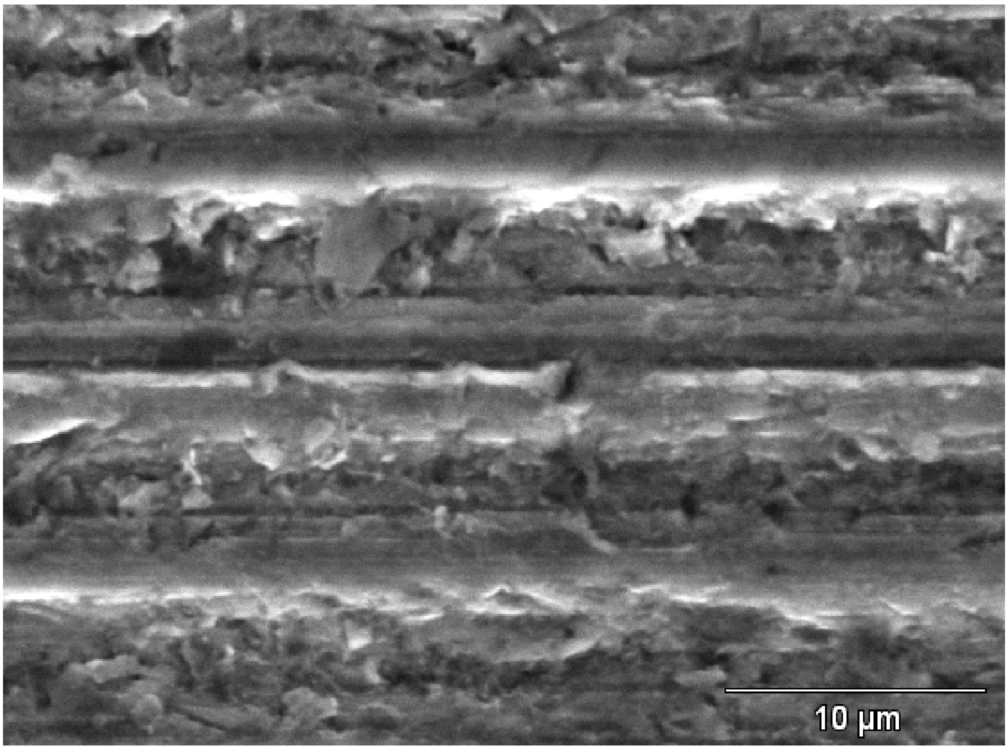

Figure 11: Wear surface of the SGCS-Laser sample

4. Conclusions

- Laser surface melting of spheroidal graphite cast steel samples resulted in a homogeneous surface layer with a very fine martensitic structure. Some retained austenite, niobium carbides and graphite nodules characterize the resulting microstructure. In the melted and heat-affected zones no pores and cracks were detected;
- The range of microhardness in the melted zone varies from 850 to 1100 HV, which is significantly higher than the hardness of the SGCS-Austempered samples (300 to 600 HV);
- Two wear mechanisms – micro-cutting and micro-ploughing – have predominantly occurred in the SGCS-Austempered and SGCS-As-cast specimens;
- For the laser treated sample, wear has occurred by micro-cutting and the resulting grooves are not so deep if compared with those observed in the wear surface of SGCS-Austempered and SGCS-As-cast specimens;
- The lower wear rate presented by the SGCS-Austempered and SGCS-As-cast specimens can be explaining by abrasive particles deeply and firmly embedded in the specimen's surface.

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