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REDUCTION OF FRICTION PROMOTED BY SURFACE TREATMENT BY CO_2 LASER IN AISI 52100 STEEL[1]

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Abstract
This study presents the results of the tribological evaluation of surface treatment by CO_2 laser in AISI 52100 steel. The study was prompted by the search for improved properties for surface materials with distinct effects on surfaces. The utilization of lasers to treat surfaces, for example fixing of carbon-coatings coatings by CO_2 laser in AISI 52100 steel at ambient atmosphere, has led to significant advances in this area. Yet, determining the operational parameters of lasers and the results of these influences on the tribological properties of the respective materials is an ongoing pursuit. The tribological tests without external lubrication confirm the existence of a laser processing range that is effective in increasing hardness and reducing friction. While the laser treated samples presented a friction coefficient of 0.3, the samples without laser treatment registered a friction coefficient on the order of 0.7. EDS chemical analyses of the zones affected by the lasers revealed short-distance atomic diffusion in the laser treated zones.
Key words: CO_2 lasers; Friction; AISI 52100 steel.

REDUÇÃO DO COEFICIENTE DE ATRITO PROMOVIDO POR TRATAMENTO DE SUPERFÍCIE VIA LASER DE CO_2 EM AÇO AISI 52100

Resumo
Neste trabalho, são apresentados os resultados da avaliação tribológica do tratamento de superfície via laser de CO_2 no aço AISI 52100. O trabalho surgiu da busca pela melhoria das propriedades superficiais dos materiais que têm solicitações diferenciadas na superfície. A utilização do laser para tratamentos de superfícies, por exemplo, fixação de revestimentos a base de carbono em atmosfera ambiente, tem possibilitado grandes avanços nesta área. No entanto, determinar quais parâmetros operacionais do laser e a resultante destas influências sobre as propriedades tribológicas dos materiais tem sido uma busca incessante. Os ensaios tribológicos sem lubrificação externa confirmam que existe uma faixa de processamento laser eficaz no aumento da dureza e na redução do atrito. Onde as amostras tratadas com laser apresentam um coeficiente de atrito da ordem de 0,3 enquanto, em amostras sem tratamento laser, o atrito é da ordem de 0,7. As análises químicas por EDS das zonas afetadas pelo laser demonstram uma difusão atômica de curto alcance nas zonas tratadas com o laser.

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1 INTRODUCTION

AISI 52100 steel is the most widely used material in the production of bearings due to its hardenability, high hardness (61 – 63 HRC), and tensile strength (2200 MPa).[1-3] However, the wear normally associated with increased friction limits its performance, leading to premature failure.[4] A recent method used to mitigate these effects in carbon steels and alloy steels involves laser surface treatment.[5-9] Through a single process, it is possible to promote changes in mechanical properties, including hardness[9] and friction,[10] and, further fixing using materials with different surface substrate properties.[11] In regard to laser processing of materials, only the portion of electromagnetic radiations absorbed by the sample is of interest.[12,13] For example, in a sample treated with CO_2 lasers (λ=10.6 μm), the reflection for metallic surfaces (ambient temperature) is on the order of 90%. To compensate for this disadvantage incident radiation photo-absorbents are applied, such as graphite, molybdenum disulphide, and carbon black, in the form of a paint coating on the processed surface.[13] Innumerable studies[9,10.11,14,15] report the use of high-powered lasers (0.5 kW – 4kW) for carbon deposition by fusion. However, Vasconcelos et al.[11] irradiated samples of AISI M2 steel by means of the utilization of a 50W CO_2 laser, without causing fusion and confirmed fixing of the graphite coating on the metal surface, with accompanying tribological tests indicating a reduction in the friction coefficient of nearly 3 times and, additionally, an increase in surface hardness of approximately 30% along a 70 μm extension. In the light of these results and given the absence of works in the literature utilizing 50W lasers for surface treatment in AISI 52100 steel, the present study proposes fixing of a carbon coating to the generation of a thermally affected zone in AISI 52100 steel, without causing surface ablation or fusion, while additionally evaluating the morphology of the fixed surface layer.

To achieve this objective, identification of the laser parameters was required, including: scan speed, number of heating cycles. As such, to contribute toward development, a variety of techniques were used, among them: Vickers microindentation hardness to test for changes in mechanical properties, SEM, used to determine the morphology of the graphite layer, EDS, for analysis of the laser treated zones, and tribological friction tests, without any type of external lubrication, for example, oil, for purposes of evaluating performance and behavior.

2 MATERIALS AND METHODS

The experimental methodology used in this study was divided into separate stages: the first referred to preparation of the AISI 52100 steel samples. The second stage consisted in preparation of a graphite solution base and recoating of the surface by means of spraying. The third stage involved irradiating the samples with a CO_2 laser flash. The fourth stage encompassed determining the coating surface and the transversal section, with or without laser treatment.

2.1 Preparation of the AISI 52100 Steel Samples

The AISI 52100 steel samples were prepared in cylindrical form (diameter 15 x 3 ± 0.1 mm) with hardness standardized at 670 $HV_{0.1}$ (after quenching and tempering). The sample surface was corrected and subsequently sanded with silicon carbide abrasive paper (600 grain size).

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2.2 Preparation of the Graphite Solution and Surface Coating

The particulate material used in the study was obtained from ground graphite particles with an average size of 3 µm. An alcohol and graphite solution was utilized and sprinkled on the surface by means of spraying. This method was selected due to easy reproduction and its wide dissemination in the literature.(11,13,14)

2.3 Surface Irradiation

A CO_2 laser device was utilized with a 10.6 µm wavelength (λ), continuous waveform (CW), flash diameter on the focus part measuring approximately 300 µm, focal distance of 190 mm, TEM_{00} mode, 50W of power, excitation by radio frequency and water cooling. Galvanometric mirrors coupled to laser tubes were responsible for the movement and direction (x, y) of the laser flash on the treated surface. A schematic of the treatment is presented in Figure 1.

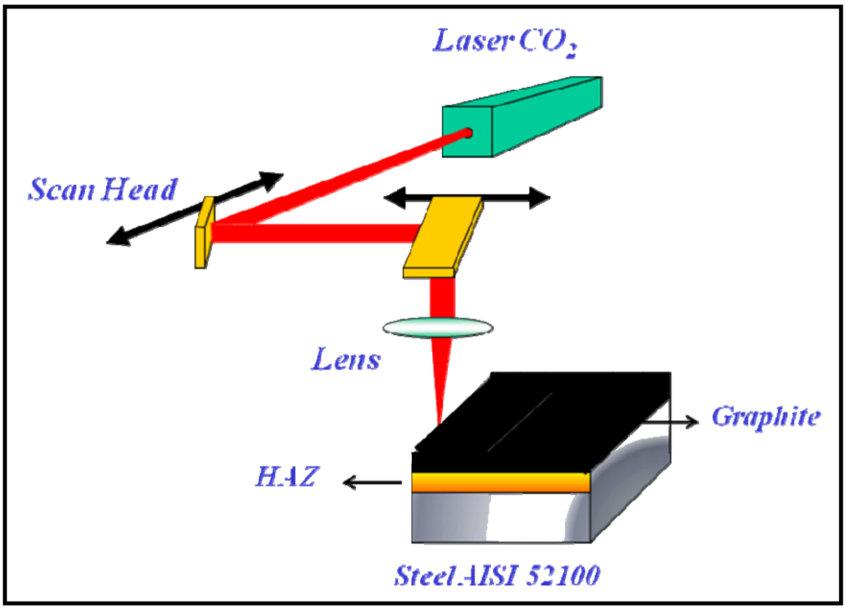

Figure 1: Schematic of AISI 52100 steel laser processing.

During irradiation of the graphite coated metal surface, the following may occur:

- Vaporization of the upper graphite layers;
- Fusion and sintering of the graphite layers;
- Heat transference to the substrate;
- Vaporization, fusion, and sintering of the graphite, heat absorption and transmission, and, consequently, HAZ-generation.

The laser processing parameters, including scan speed (10 to 200 mm/s) and number of heating cycles (1, 2, 5) were tested to evaluate the optimal conditions for fixing of the coating without causing damage (fusion or ablation) on the surface and generating a heat treated area. The launch point for the tests centered on the scan speeds, followed by the combination of heating cycles.

2.4 Techniques

Following irradiation of the AISI 52100 sample, the degree of fixing of the graphite coating was evaluated through rubbing of the surfaces with metallographic cloths. The samples were then cleaned in ultrasound baths with distilled water and acetone p.a. baths for 30 minutes. The samples were stored in a hermetically sealed vacuum container to prevent contamination.

To evaluate the extension of the heat-affected zone (HAZ), conventional sample preparation techniques were used, such as: sectioning, thermoforming, sanding, polishing, chemical attack with Picral (2%), and observation by optical microscope.

The morphology of the coating was accomplished by means of Scanning Electronic Microscopy (SEM) and chemical analysis of the EDS treated zones.

The hardness profiles were evaluated by means of Vickers microindentation (0.1 kg load in 9 seconds) at the transversal section of the samples, based on the extension of the laser treated zone.

The friction tests were performed using a Nanovea pin-on-disc tribometer, with test pairs (pin and disc) of AISI 52100 steel, with and without laser treatment. The rotational movement (150 rpm - 78.5 mm/s) occurred in an ambient atmosphere with controlled temperature and humidity (20ºC ± 1 and HR=50% ± 5), and a normal applied load set at 10N. The friction coefficient (μ) was measured by means of a load cell and the data processed by dedicated software installed in the device. No external lubricants of any kind, such as oil, were utilized in the tests. In addition, the surface of the pin (a 6 mm diameter ball) remained fixed during each experiment, and a different region of the ball was employed in each new test (ball didn't received any laser treatment).

3 RESULTS AND DISCUSSION

3.1 Microstructure of AISI 52100 Steel without Laser Treatment

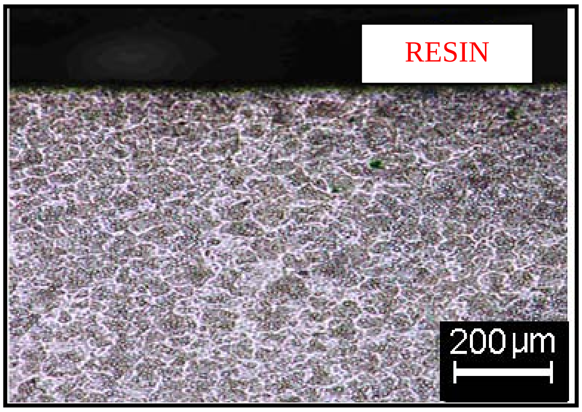

Figure 2: Microstructure of AISI 52100 steel, consisting of two distinct stages.

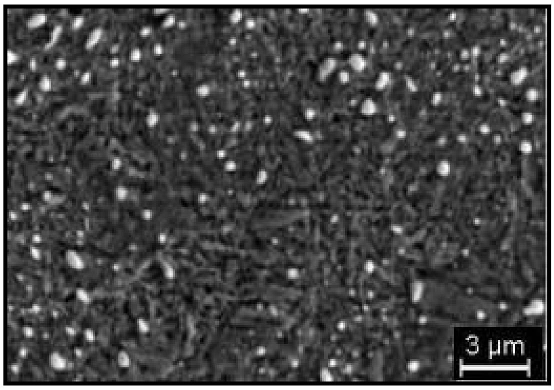

Figure 3: SEM of AISI 52100 steel, consisting of two distinct stages.

Figures 2 and 3 present the optical microscopy and SEM, respectively, of the AISI 52100 steel under quenching and tempering treatment conditions. A martensitic matrix with spheroidized carbon was observed.[1-3]

3.1.1 Microstructure of AISI 52100 steel with laser treatment

After numerous experiments, full evaporation of the graphite layer and surface damage (fusion or ablation) was observed in the laser-irradiated samples with velocities below 10 mm/s and a high number of heating cycles (5) revealed, as shown in Figure 4. The irradiated samples with a low number of heating cycles (2) and velocities from 30 to 100 mm/s demonstrated fixing of the coating and expansion of the thermally treated zone.

In terms of energy balance, Fluence (energy by area) above 11 x 10^6 J/m^2 cause ablation while energies of 3 x 10^6 J/m^2 allow for treatment of the material. However, energies below 3 x 10^6 J/m^2 do not enable fixing of the coating.

Figures 4 and 5 lay out the transversal section of AISI 52100 steel after laser treatment.

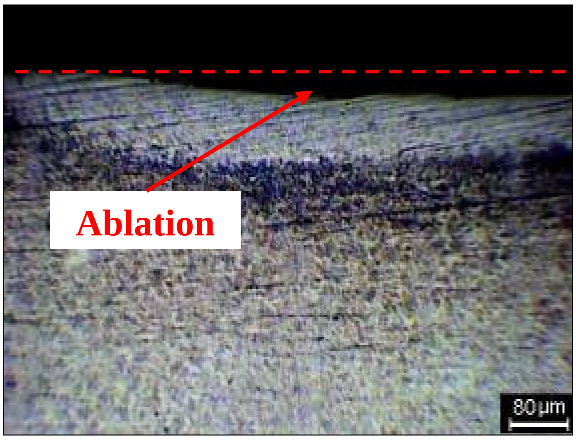

Figure 4: Transversal section of the laser treated zone (with ablation) and the base of the material, 2% Picral reagent.

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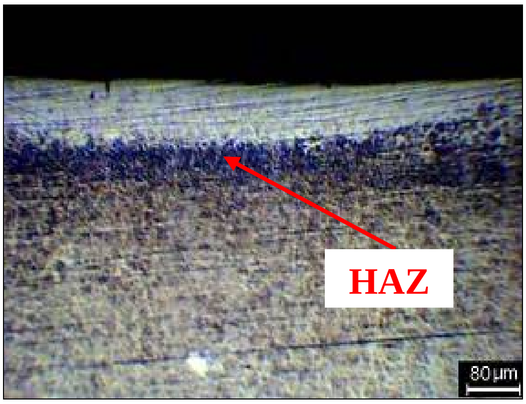

Figure 5: Transversal section of the laser treated zone (without ablation) and the base of the material, 2% Picral reagent.

3.2 Vickers Microindentation Hardness Profile

The microindentation points were performed transversally to the laser treated zone, distributed so as to encompass the heterogeneities of the samples and in this way enable comparisons between the different regions. Figure 6 presents the Vickers hardness profiles for the laser treated samples with three different conditions, namely Fluence of 3, 7, and 11 J x $10^6/m^2$.

Using a Fluence of 11 J x $10^6/m^2$, a depth of 65 µm was measured for the treated zone and a surface hardness on the order of 1040 $HV_{0.1}$ ± 50. After reducing the energy delivered to the procedure, the depth of the treated zone was approximately 65 µm and the surface hardness 1020 $HV_{0.1}$ ± 42. Through a further reduction in energy, the depth (or extension) of the treated zone stood on the order of 20 µm and surface hardness reached 890 $HV_{0.1}$ ± 30. The extension of the zone varied in accordance with the energy employed. That is, the greater the energy, the greater the hardness. However, the process is constrained by ablation or fusion of the material.(14,15)

Increased hardness is due to rapid heating and cooling by laser(14,15) and carbon diffusion in the graphite layer on the metal surface.(11,14)

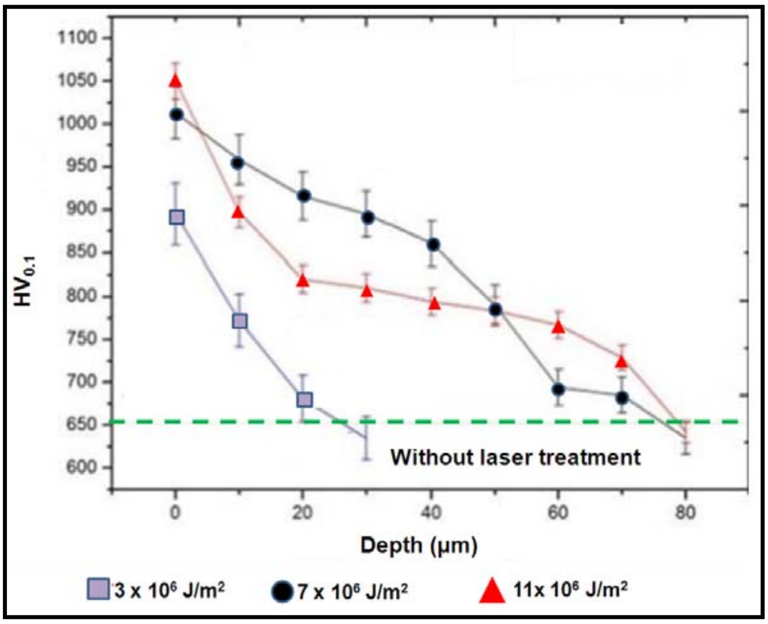

Figure 6: Profile obtained from Vickers microindentation of the laser treated zones using different energy intensities.

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3.3 SEM of the Coating

The graphite coatings fixed by the laser treatments were observed by means of SEM (Figure 7). Due to the similarity of the process only the coating surface fixed with energy of 7 x 10^6 J/m^2 is presented here.

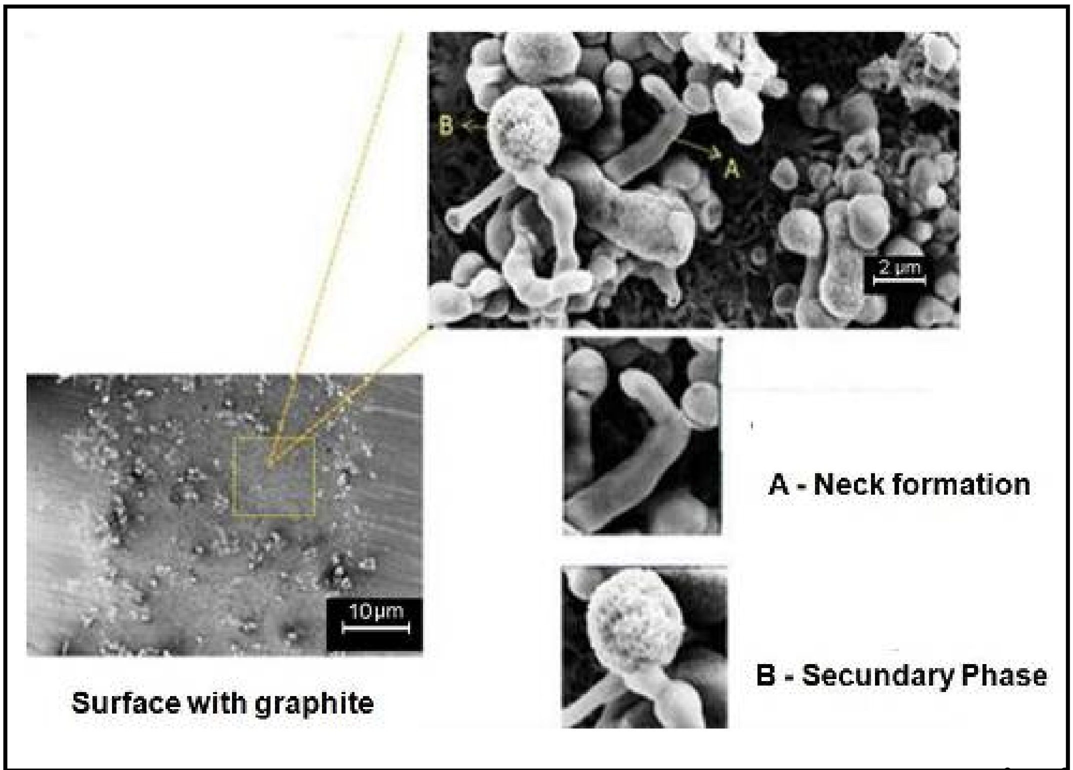

Figure 7: Morphology of the graphite coating fixed with an energy intensity of 7 x 10^6 J/m^2.

In Figure 7, the coating is fixed on the steel surface. The edges reveal the marks of the abrasive paper (600) utilized during preparation of the sample. Analysis of the expansion of the laser irradiated region allows for observation of the graphite coating morphology during sintering in two distinct stages: Stage (A) in which the graphite particles link together (neck formation), and Stage (B), representing the intermediate step of the process. Graphite sintering is promoted by the action of the laser.

3.4 Chemical Analysis by SEM

This section discusses aspects of the surface laser treatment (Fluence 7 x 10^6J/m^2). The test was performed by means of EDS coupled to SEM. The spectrum of chemical analysis was accomplished at the transversal section of AISI 52100 steel, as shown in Figure 8.

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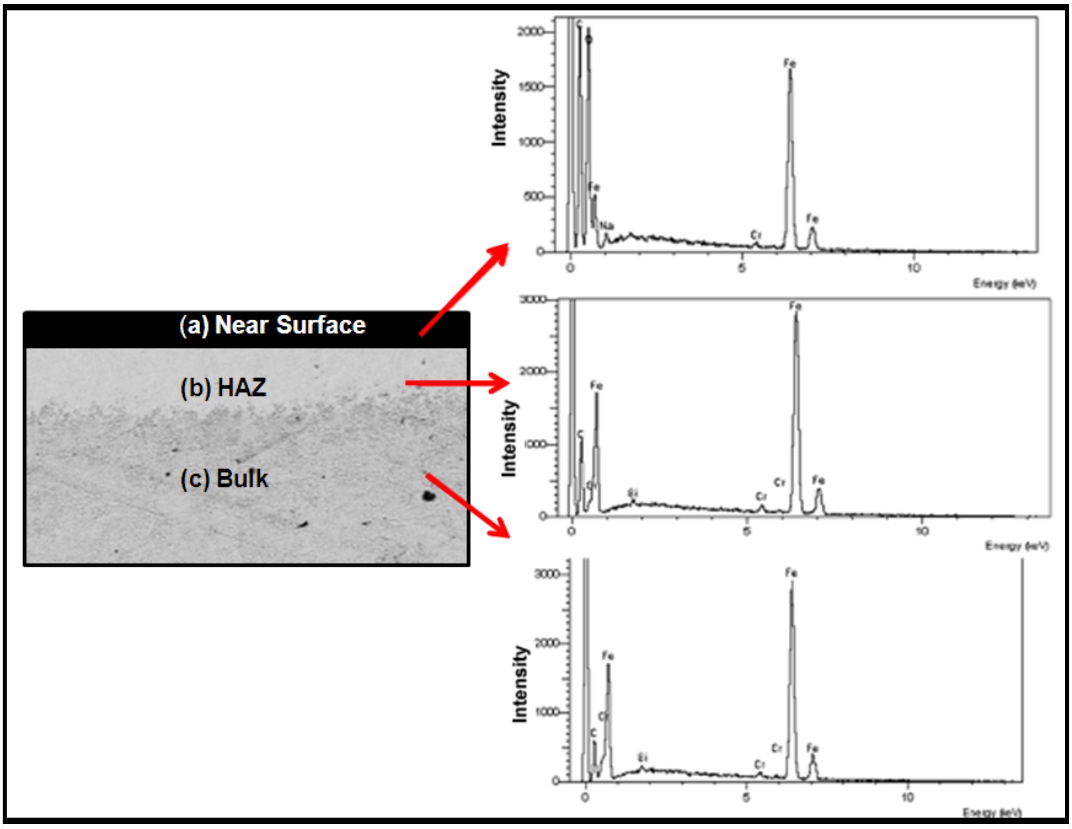

Figure 8: Chemical analysis of the transversal profile of laser treated AISI 52100 steel.

The carbon concentration is observed to vary from one region to the other. In the region nearest the surface (a) the carbon intensity is high. This is due to the graphite coating. Region (b) is the HAZ (heat-affected zone) by laser, where a reduction in intensity is observed. Region (c) represents the point at which the substrate remains unaltered. This fact is related to the short-distance carbon diffusion promoted by the laser.

3.5 Friction Coefficient

The pairs evaluated in the tribological test were:

- AISI 52100 pin (ball) submitted to quenching and tempering treatment with hardness of 730 $HV_{0.1}$.
- AISI 52100 disc with laser treatment irradiations of: 3, 7, and 11 x 10^6 J/m^2.
- Number of rotations: 2000
- Applied load: 10N.
- Without external lubrication.

The friction coefficients for the evaluated pairs were obtained by means of dedicated software. Figure 9 presents the results.

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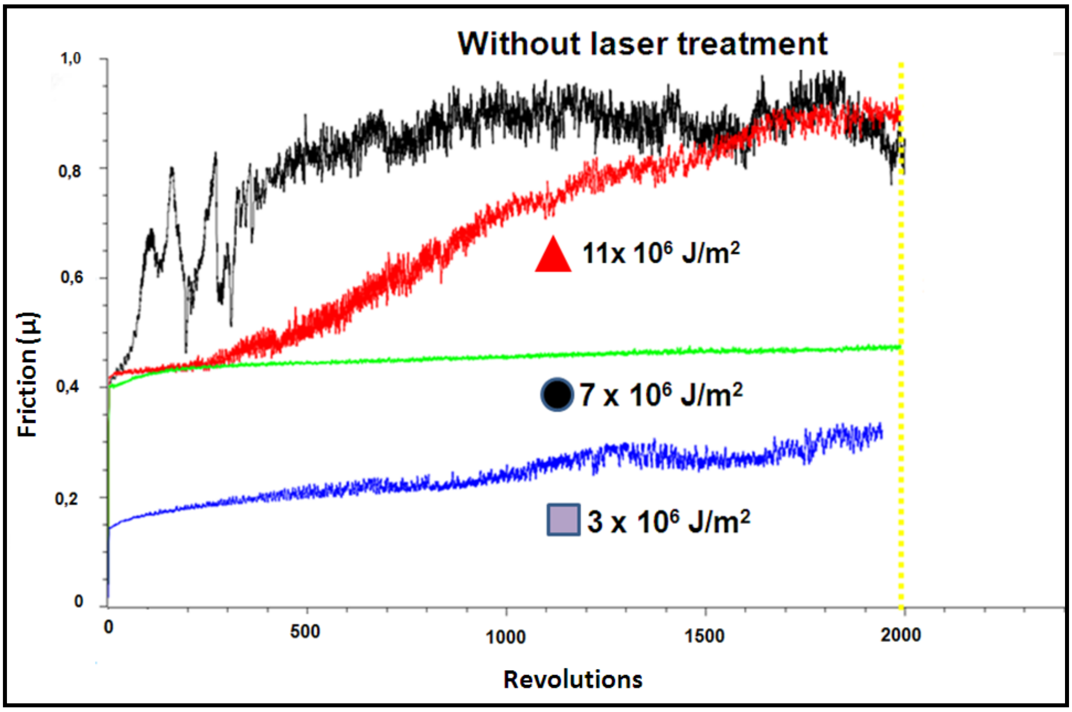

Figure 9: Results for the friction coefficients of samples with and without laser treatment.

In examining the curve for the pair without laser treatment, softening of the contact surfaces was verified in the beginning stages of the test (500 revolutions). Yet, the friction coefficient registered values of 0.7 – 0.8 through conclusion of the test.

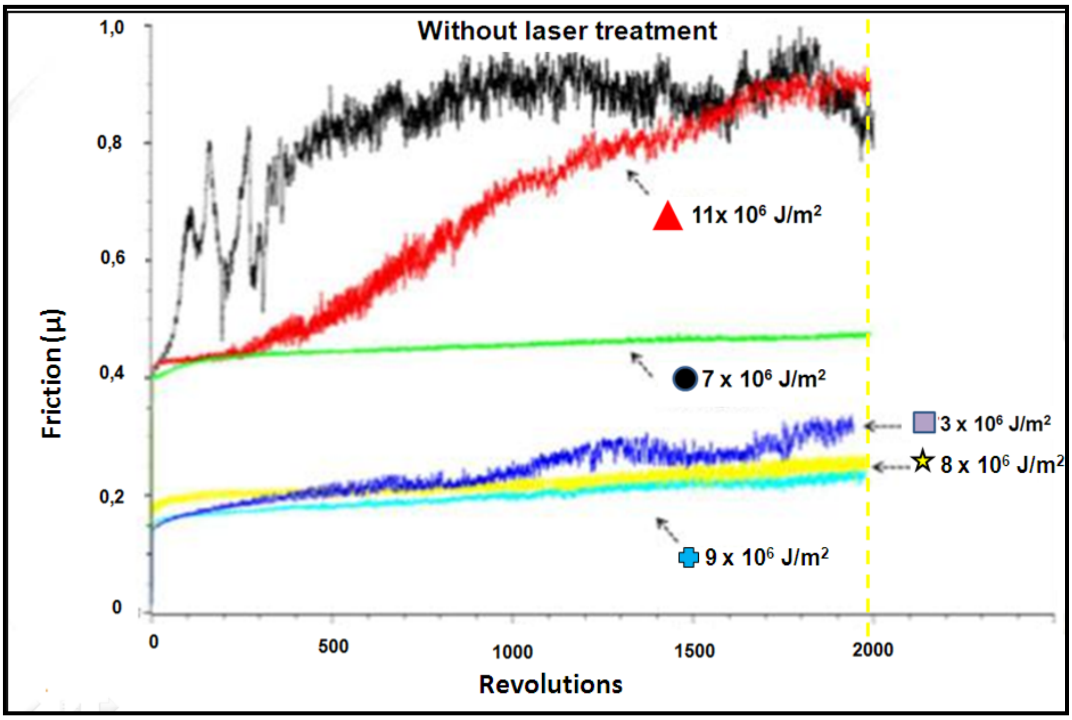

Figure 10: Friction coefficient for the laser treated pairs.

Evaluation of the friction coefficient for the pair with laser treatment (11×10^6 J/m^2) revealed friction coefficient values of 0.4 – 0.6. This finding was expected due to the graphite coating. However, after 1000 revolutions the coating

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breaks and the friction coefficient rises to levels equivalent to the values observed in the pair without laser treatment.

The friction coefficient for the pair irradiated at 7 x 10^6 J/m^2 was 0.4, remaining unaltered throughout the test.

The friction coefficient for the pair irradiated at 11 x 10^6 J/m^2 was on the order of 0.2. To further refine the process and evaluate the maximum achievable friction reduction, two new tests were performed. The laser irradiation parameters were 8 and 9 x 10^6 J/m^2. Figure 10 presents the results for these parameters.

The friction coefficient for the pair irradiated with 8 x 10^6 J/m^2 was less than 0.2. By contrast, in the test using 9 x 10^6 J/m^2 the friction coefficient registered a slight increase. This finding leads to the conclusion that there is a threshold reduction in the friction coefficient for the evaluated pairs. That is, the friction coefficient for the pairs treated with lasers remains within a range from 0.2 to 0.4.

4 CONCLUSIONS

The analysis focused on the performance of studies regarding the tribological behavior of AISI 52100 steel treated with a 50W CO_2 laser using different processing parameters. Taking into account the objectives of the analysis, the following conclusions can be drawn from the study:

1 – It is possible to prevent surface fusion or ablation, fix a layer of graphite coating within an ambient atmosphere, and generate a HAZ, thereby corroborating the work of Vasconcelos et al.(11)

2 – The hardness achieved in the laser treated zones was on the order of 1040 $HV_{0.1}$, with slight gradients and extremely short times when compared to conventional treatment methods, for example cementation.(16)

3 – The HAZ formed by the laser treatment register an increase in carbon concentration, as identified in the chemical analysis (EDS). This increase indicates a short-distance diffusion process.

4 – The tribological evaluation indicates a reduction in the friction coefficient for the laser treated pairs when compared to the non-laser treated pairs. However, we cannot affirm categorically that other conditions with similar characteristics beyond those evaluated do not exist.

5 – The graphite coating arising from contact with surface roughness may be removed by generating a third body.(17) However, it is worth underscoring that the interposition of a soft body contributes to running-in of the surfaces.

6 – The analysis represents a promising step toward improving the mechanical (hardness) and tribological (friction) properties of AISI 52100 steel, and as well as an innovative effort, insofar as no other works were identified in which a 50W CO_2 laser was utilized to promote the related enhancements in AISI 52100 steel.(1) Nonetheless, additional detailed studies are required under conditions more closely approaching real-life applications.

REFERENCES

1 H.BurrierJr.,in: ASM Handbook (1), ASM International, Materials Park, OH,1997, pp.380–388.

2 Heat-treated Steels, Alloy Steels and Free-Cutting Steels–Part17: Ball and Roller Bearing Steels, ISO 683-17, 1999.

3 J.J.C.Hoo, Creative Use of Bearing Steels, ASTM International, West Conshohocken, PA,1993.

ISSN 2179-3956

4 BASU, A. et al. Laser hardening of austempered (bainitic) ball bearing steel. Surface & Coatings Technology Scripta Materialia, v. 56, n. 10, p. 887 – 890, 2007
5 KAUL R. et al. Characterizationof dry sliding wear resistance of laser surface hardened En 8 steel. Journal of Materials Processing Technology v. 167 p. 83–90, 2005.
6 D.I.Pantelis et al. Wear and corrosion resistance of laser surface hardened structural steel. Surface and CoatingsTechnology v.298, p 125–134, 2002.
7 J.Grum et al. The influence of different conditions of laser- beam interaction in laser surface hardening of steels. Thin Solid Films v.453–454, p. 94–99, 2004.
8 YAO, Jianhua, et al. Microstructure and wear property of carbon nanotube carbon steel by laser surface remelting. Applied Surface Science. Surface Science , p. 811–814,2006.
9 GANEEV, R.A. Low-power laser hardening of steels. Journal of Materials Processing Technology, v.121, n. 2/3, p. 414–419, 2002.
10 KATSAMAS, A.I. Laser-beam carburizing of low-alloy steels. Surface & Coatings Technology, v 139, p.183-191. 2000.
11 VASCONCELOS, G et al. Thermal treatment of the AISI M2 high speed steel promoted by CO_2 laser beam. Materials Science Forum, v. 591-593, p 62 - 67. 2008
12 READY, John F.; FARSON, D. F.; FEELEY, T (Ed.). LIA handbook of material processing. Orlando: LIA, 2001.
13 CHARSCHAN, S. S. Lasers in industry. New York: Van Nontrand Reinhold Company,1972.
14 Chiang KA, Chen YC. Laser surface hardening of H13 steel in the melt case. Mater. Letters v. 59(14-15), p1919-1923, 2005.
15 VISSCHER, H. et al.The influence of laser line hardening of carbon steel AISI 1045 on the lubricated wear against steel AISI 52100. Wear, v. 181-183, p. 638-647, 1995
16 SANDOR, L. T. A model for fracture toughness evaluation of the carburized layer for SAE 5115 steel. 153 f. master's degree (Mechanical Engineering) – Unicamp, Campinas. 2005.
17 CLAUS , F.J Solid lubrficants and self-lubricating solids. Nesw York: Academic Press, 1972 .