V.25 N.02
REVISTA MATÉRIA
ISSN 1517-7076 articles e-12618, 2020

Influence of residual stress on the sliding wear of AISI 4340 steel

Ítalo do Valle Tomaz [2], Mateus Campos Martins [1],
Hector Reynaldo Meneses Costa [3], Ivan Napoleão Bastos [4],
Maria Cindra Fonseca[1]

[1] Laboratório de Análise de Tensões - LAT– TEM/PGMEC/UFF, Rua Passo da Pátria, 156, São Domingos, CEP: 24210-240, Niterói, RJ, Brazil.
e-mail: mcindra@vm.uff.br, mateuscampos@id.uff.br
[2] Instituto Federal Fluminense - Estrada Cabo Frio - Búzios, s/nº, CEP: 28909-971, Cabo Frio, RJ, Brazil.
e-mail: italo.tomaz@iff.edu.br
[3] Centro Federal de Educação Tecnológica Celso Suckow da Fonseca - Av. Maracanã, 229, CEP: 20271-110, Rio de Janeiro, RJ, Brazil
e-mail: hectorey@cefet-rj.br
[4] Universidade do Estado do Rio de Janeiro - Rua Bonfim, 25, CEP: 28625-570, Nova Friburgo, RJ, Brazil.
e-mail: inbastos@iprj.uerj.br

ABSTRACT

Mechanical components and structures wear out as a result of friction between surfaces in relative motion. Residual stresses play an important role for the tribological performance of components since compressive residual stresses yield positive effects on wear resistance. However, the real effect of residual stresses on the tribological performance of surfaces is not entirely clear. The objective of this work is to evaluate the residual stress behavior during a pin-on-disk wear test of quenched and tempered AISI 4340 disk specimens against a counter-body of steel AISI E 52100. Tests were performed in shot peened and non-shot peened specimens in six steps and residual stresses were evaluated after each one by X-ray diffraction technique using $sin^2\psi$ method. The results shown that wear rate of the shot peened specimens was approximately fifty percent lower. Shot peening induced compressive residual stresses contributed to this effect even though they were modified during the pin-on-disk test.

Keyword: Residual stress, X-ray diffraction, AISI 4340 steel, Wear, Pin-on-disk test, shot peening.

1. INTRODUCTION

Sustainable development is one of the biggest challenges of century XXI and it is changing many industrial processes. In this new model of development, it is essential to improve the usage of natural resources and energy. Designing and manufacturing more durable machines and components contribute to the rational use of natural resources. Wear represents one of the biggest issues to component lifespan [1,2] thus, it is necessary to improve component wear resistance.

AISI 4340 steel is a low-alloy martensitic steel widely-used as machine part-members due to its combination of strength, ductility and toughness [3-5]. Most of these components are submitted to cyclic load during its life. Shot peening (SP) has long been a conventional surface mechanical treatment used to improve fatigue resistance of high-performance components in the structural and aircraft industries [6], which can generate an effective field of compressive residual stresses [7,8]. Although the influence of residual stresses in components fatigue life is already well stablished its influence effect in wear behavior is not completely understood [9].

Totik *et al*. [1] employed induction hardness treatment to introduce compressive residual stress in AISI 4140 steel. Moreover, laser peening has been used to obtain similar results [10,11]. In these studies, the heat input was high enough to cause microstructural and consequently hardness changes. Considering that hardness and microstructure have influence in wear rate [7,12,13], it is not a simple task to evaluate separately the influence of residual stress in the experimental wear rates.

The objective of this work was to evaluate the influence of residual stress in the wear mechanisms and wear rate of AISI 4340 steel submitted to pin-on-disk test. To avoid any microstructure and hardness changes

Autor Responsável: Ítalo V. Tomaz Data de envio: 26/11/2018 Data de aceite: 07/06/2019

10.1590/S1517-707620200002.1018

compressive residual stresses were introduced by shot peening instead of induction hardness or laser peening.

2. MATERIALS AND METHODS

2.1 Specimens preparation and hardness tests

Disk specimens of AISI 4340 steel, diameter 50.8 mm x thickness 6.0 mm (Figure 1), were cut from an original rolling bar using an abrasive cutter. Chemical composition of the AISI 4340 steel is presented in Table 1.

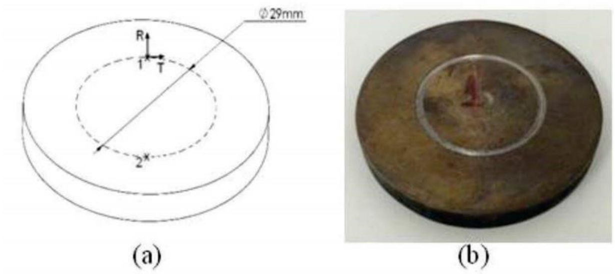

Figure 1: AISI 4340 disks used in wear tests: (a) Dimensions; (b) Worn surface.

Table 1: Chemical composition of steel AISI 4340 (wt%).

C	Si	Mn	P	S	Cr	Ni	Mo	Fe
0.39	0.25	0.72	0.01	0.025	0.75	1.72	0.24	Balance

The disks were submitted to austenitizing at a temperature of 860 °C for 60 minutes and subsequently oil quenched. Then, all the specimens were tempered at a temperature of 300 °C for 90 minutes. After the heat treatments half of them were submitted to shot peening to introduce compressive residual stresses in surface and subsurface. Four replicas were used in each condition (shot peened and non-shot peened).

The shot peening mechanical treatment was performed at Almen intensity (A) of 0.25 A determined according with SAE J442 specification 7, Grade II, type "C" Almen strips were used firmly screwed to Almen blocks. The arcs generated in the strips were measured using an Almen gage provided by a magnetic support system with an uncertainty of 0.001 mm.

Vickers Microhardness, applying a load of 48 N during 15 seconds, was performed in the section of specimens to investigate any hardness change due to shot peening surface treatment. To concentrate the wear in the disk, AISI E 52100 high hardness steel spheres with 6.0 mm of diameter and 796 HV 0.5 N was chosen as counterbody.

2.2 Wear tests

Pin-on-disk tests were performed at room temperature in dry conditions. All sliding wear tests were conducted under constant load of 10.18 N and constant speed (tangential speed) of 91.1 mm/s. The values of these parameters were selected according to the results of previous experiments which investigated the minimum load and speed to produce a measurable wear track.

Tests were performed in six steps of 3600 cycles. Each step corresponds to a travelled distance of 328 m. The total distance, after the six steps, is 1928 m. At the end of each step, the experiment was interrupted, the worn specimen was removed, and the residual stresses of the wear track were evaluated. A typical specimen with wear track is shown in Figure 1b. Parameters set and samples preparation were selected to ensure that the only significant difference between the two groups was the previous residual stress state and that other parameters, such as hardness and microstructure, would not influence in test results as reported in other works [1,10,11].

The wear coefficient (k) was calculated using the Archard [14] equation that takes the form k=V/N.L. Where V is wear volume, N is the normal load and L is the sliding distance. To calculate the wear volume, after the sixth step (1928 m), the profiles were recorded by a Mitutoyo profilometer in two points on the track and located in the diameter (points 1 and 2 of Figure 1a). The wear volume was calculated by multiplying the track area by its mean perimeter. Surface topography analysis of the worn surface was imaged using optical microscopy and scanning electron microscopy - SEM to identify the main wear mechanisms.

2.3 Residual stress measurements

Residual stresses measurements were carried out by X-ray diffraction technique using $\sin^2\psi$ method and incremental layer removal by electropolishing. A XSress3000 (Stresstech) stress analyzer was used with a CrKα (λ = 2.29092 Å) radiation source diffracting the (211) plane. Residual stresses were measured at two points located in the diameter of tracks (points 1 and 2 of Figure 1.a) in the radial (R) and tangential (T) directions. Measurements were performed in all samples before the first the beginning of wear tests and after each step.

The removal layer method by electrolytic polishing was used to obtain the profile of residual stress variations through the thickness of the disk, which consists on the electrolytic removal of the metal on a high ionic solution by means of electrical potential and current. As electrolyte was used a sodium chloride saturated solution with glycerin, and the voltage and current parameters were 30 V and 0.20 A, respectively. The depth of the removed layer was measured with a digital comparison gauge.

3. RESULTS AND DISCUSSION

3.1 Microstructure and Hardness evaluation

The sample microstructure, comprised of tempered martensite is show in Figure 2. An average surface hardness of 490 ± 12 HV 0.5 N was found.

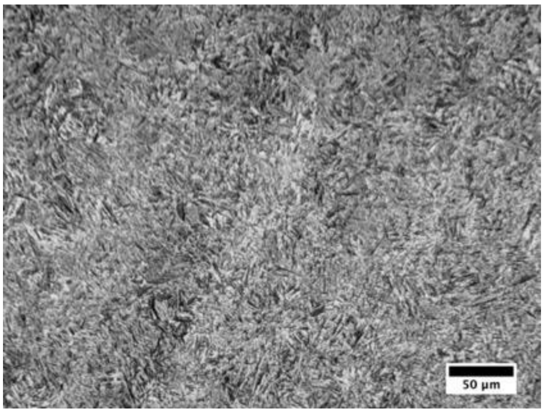

Figure 2: Tempered martensite microstructure. Optical microscopy.

Figure 3 presents Hardness vs. Depth curves for shot peened and non-shot peened conditions. These results represent the mean value obtained from the four shot peened samples. Maximum hardness values were obtained in specimen surface as a consequence of quenching treatment. The difference between shot peened and non-shot peened specimens agrees with the result presented by Llaneza and Belzunce [15] of shot peened AISI 4340 steel with several conditions produced hardness increases below 11 %. Same results were reported by Zhang *et al.* [16] whose work evaluated the effect of shot peening in 17CrNiMo6 steel. These results were decisive to exclude the influence of hardness in the difference between the wear rates of the two groups.

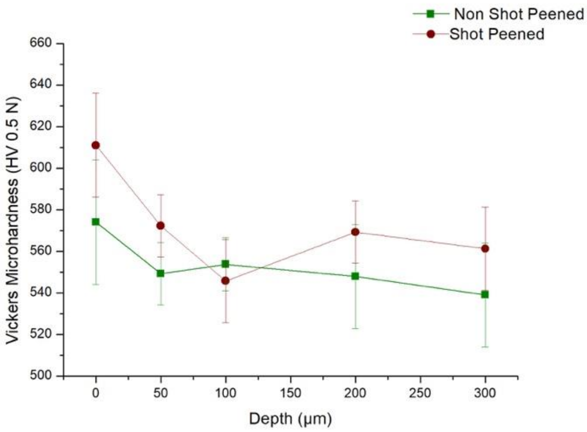

Figure 3: Microhardness profile.

3.2 Residual stresses

To confirm the effectiveness of shot peening treatment the residual stresses were measured in shot peened and non-shot peened specimens. Figure 4 shows the mean residual stress profile of both conditions.

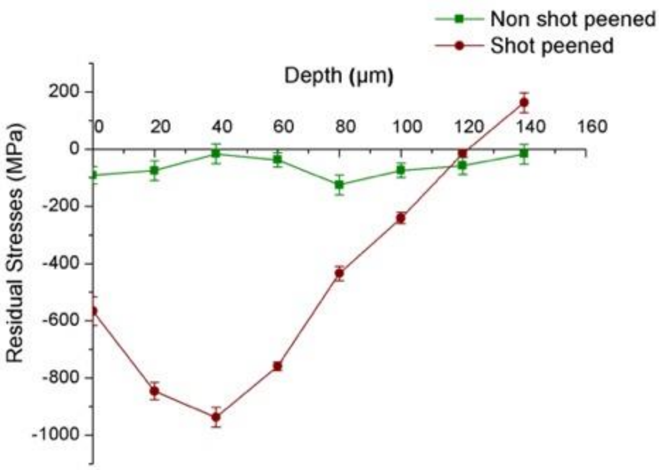

Figure 4: Depth residual stress profile before wear tests.

As reported by Llaneza and Benzunce [15] and residual stresses reach the maximum compressive values in subsurface region, around 40 µm. Residual stresses in the wear track were measured before the tribological tests and after each step. The progress of residual stresses during pin-on-disk test is depicted in Figures 5 and 6 using the average values of each group.

Before the rubbing, it is possible to observe a great effect of shot peening on residual stress. Along the travelling distance, the stress values seem to converge. This effect is greater in tangential direction which is the test sliding direction. It reinforces the hypothesis that the stresses introduced by wear test tend to superpose the previous stress state, which was also observed by Pyzala *et al.* [17]. Despite that, the 1928 m traveled during tribological test were not able to completely superpose the residual stresses introduced by shot peening process in the samples, which remained compressive even after the tribological efforts.

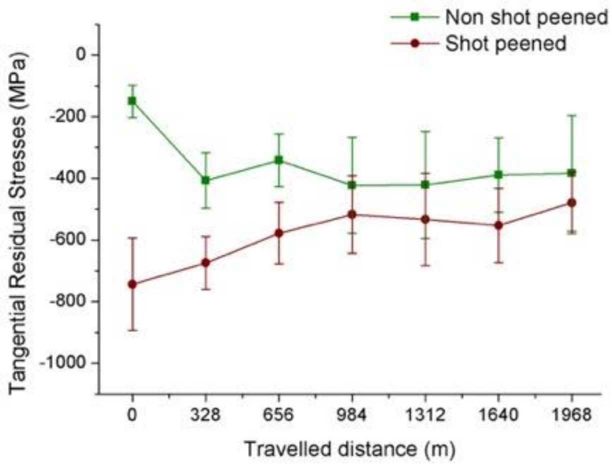

Figure 5: Tangential residual stresses during pin-on-disk test.

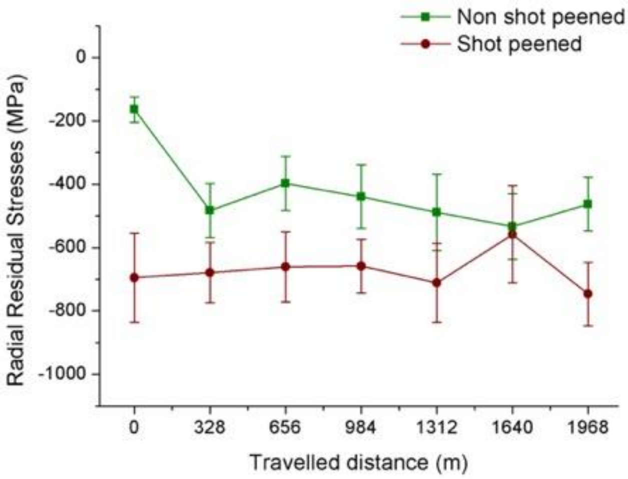

Figure 6: Radial residual stresses during pin-on-disk test.

3.3 Worn surface characterization

Figure 7 shows the worn surface optical micrograph after 1928 m distance. Deeper and regular wear scars can be observed in non-shot peened specimens (Figure 4.b). These scars are the evidence of abrasion [18,19], which is the main wear mechanism, along with the formation of layer patches and some delamination regions. Lorenzo-Martin and Ajayi [20], whose work evaluated the tribological performance of surface hardened AISI 4140 steel, reported a very similar behavior for non-treated specimens. However, shot peened specimens suffered more severe adhesive wear, especially in the sides of wear track as observed by Totik *et al*. [1].

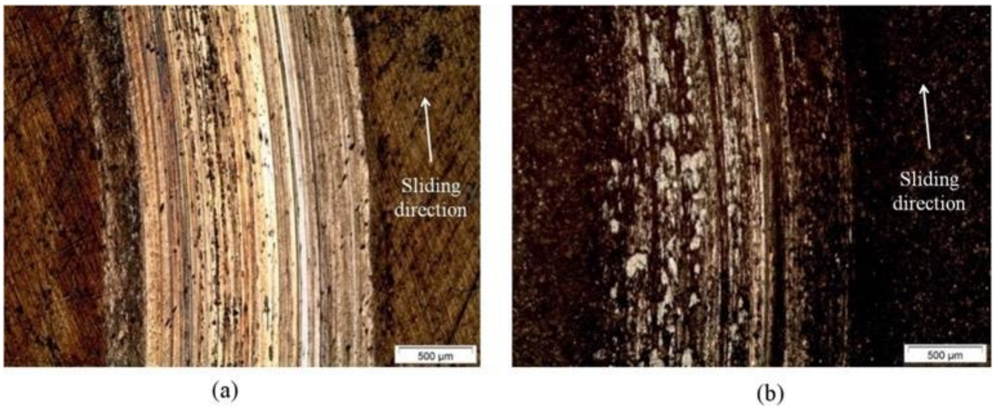

Figure 7: Optical micrography of the wear track (1928 m travelled): (a) Non-shot peened specimen (b) Shot peened specimen.

The wear tracks, also analyzed by SEM, are shown in Figure 8. A delamination crack can be observed in non-shot peened specimen. According to the delamination theory of wear by Suh [21], when sliding surfaces are submitted to cyclic loads the surface traction exerted by harder asperities on softer surfaces induces plastic shear deformation which accumulates with repeated loading and cracks are nucleated, especially in subsurface layers. Once cracks are present, they tend to extend and propagate parallel to the surface when they finally shear to the surface long and then wear sheets delaminate [21-23].

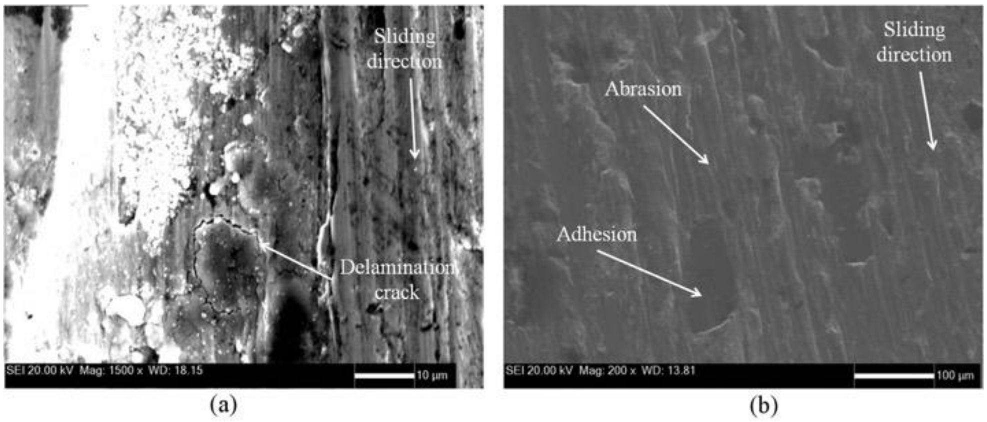

Figure 8: SEM micrography of wear track (1928 m travelled): (a) Non-shot peened specimen (b) Shot peened specimen.

Considering shot peening process introduced high compressive residual stress in surface and subsurface layers it is possible to conclude that the existence of compressive stress state delayed the propagation of subsurface cracks and inhibited the delamination wear mechanism. Similar results were obtained by Yakimets *et al.* [11] when 100Cr6 specimens submitted to laser peening treatment presented lower wear rates than untreated.

3.4 Wear rate

Average wear rate of shot peened specimens is 46 % lower than the average wear rate observed in non-shot peened specimens as shown in Table 2.

Table 2: t-Student evaluation for wear rate.

	Average wear rate	Variance $(mm^3/N.km)^2$	t-Student	t_c bi-lateral

	(mm^3/N.km)			
Non-shot peened	8.95x10^{-4}	4.31x10^{-4}	3.55	2.78
Shot peened	4.82x10^{-4}	1.12x10^{-4}		

These results show that shot peening was able to reduce the wear rates in pin-on-disk tests. Sánchez-Santana *et al*. [24] obtained a similar result comparing wear of 6061-T6 aluminum alloy treated by laser peening process and ascribed it to the compressive residual stresses introduced by laser peening process.

Considering both groups had same microstructure and very similar hardness, the great difference of their wear rates can be assigned to the high compressive residual stress state present in shot peened specimens. Compressive residual stresses were able to delay delamination wear and reduce wear rate.

To confirm the statistical significance of results a bi-lateral t-test was used with a significance level of 5 % (Table 2). Considering the calculated t value is greater than the critical significance, the null hypothesis was rejected and the difference of two wear rates is statistically significant. Hence, the shot peening effectively reduces the wear in pin-on-disk test under the studied conditions.

4. CONCLUSIONS

In this study, dry sliding friction tests were carried out to determine the influence of residual stresses on the wear performance of quenched and tempered AISI 4340 steel tested against AISI E 52100 counterbody without lubrication.

The results showed shot peening improved specimens wear behavior reducing the wear rate from 8.95x10^{-4} mm^3/N.km in non-shot peened specimens to 4.82x10^{-4} mm^3/N.km in shot peened specimens with statistical significance level of 0.05. Considering that there is no significance variation of hardness and microstructure, this great difference in wear rate can be attributed to the previously residual stress state of the two groups. The presence of residual compressive residual stresses in shot peened samples seems to delay the formations of the microcracks and consequently the delamination wear.

5. ACKNOWLEDGMENT

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – Finance Code 001. The authors would also like to thank the Brazilian research agencies CNPq and FAPERJ for the financial support.

6. BIBLIOGRAPHY

[1] TOTIK Y., SADELER R., ALTUN H., *et al*., "The effects of induction hardening on wear properties of AISI 4140 steel in dry sliding conditions", *Materials and Design*, v. 24, pp. 25–30, 2002.

[2] HOLMBERG, K., KIVIKYTÖ-REPONEN, P., HÄRKISAARI, P., *et al*., "Global energy consumption due to friction and wear in the mining industry", *Tribology International*, v. 115, pp.116-139, 2017.

[3] RAMPRASAD, M, MAYURAN, MM., "Some studies on scuffing performance of surface treated AISI 4340 steels", *Journal of Tribology*, v.125, pp.81-186, 2003.

[4] LEE, W., SU, T., "Mechanical properties and microstructural features of AISI 4340 high-strength alloy steel under quenched and tempered conditions", *Journal of Materials Processing Technology*, v. 87, pp.198-206, 1999.

[5] MEYSAMI, A.H, GHASEMZADEH, R, SEYEDEIN, S.H, *et al*., "An investigation on the microstructure and mechanical properties of direct-quenched and tempered AISI 4140 steel", *Materials and Design*, v. 31, pp. 1570–1575, 2010.

[6] WITHERS, P. J. B.H, ADESHIA, H.K.D.H., “Residual stress Part 1 – Measurement techniques”, *Materials Science and Technology*, v. 17, pp.355-365, 2001.

[7] YANG, Q, ZHOU, W, GAI, P, *et al*., “Investigation on the fretting fatigue behaviors of Ti-6Al-4V dovetail joint specimens treated with shot peening”, *Wear*, v. 372-373, pp. 81-90, 2017.

[8] MENIG, R., PINTSCHOVIUS, L., SCHULZE, V., *et al*., “Depth profile of macro residual stresses in thin shot peened steel plates determined by X-ray and neutron diffraction”, *Scripta Materialia*, v. 45., pp. 977-983, 2001.

[9] BUCIUMEANU, M, CRUDU, I, PALAGHIAN, L., *et al*., “Influence of an additional elastic stress on dry wear behavior in reciprocating tests”, *Tribology International*, v. 42, pp. 1101–1107, 2009.

[10] NARAYANASWAMY, B., HODGSON, P., BELADI, H., “Comparisons of the two-body abrasive wear behaviour of four different ferrous microstructures with similar hardness levels”, *Wear*, v. 350-351, pp.155–165, 2016.

[11] YAKIMETS, I., RICHARD, C., BÉRANGER, G., *et al*., “Laser peening processing effect on mechanical and tribological properties of rolling steel 100Cr6”, *Wear*, v. 256, pp.311–320, 2004.

[12] TANG, L., GAO, C., HUANG, J., *et al*., “Dry sliding friction and wear behaviour of hardened AISI D2 tool steel with different hardness levels”, *Tribology International*, v. 66, pp. 165–173, 2013.

[13] MODI, A.P., “Effects of microstructure and experimental parameters on high stress abrasive wear behavior of a 0.19wt%C dual phase steel”, *Tribology International*, v. 40, pp.490–497, 2007.

[14] ARCHARD, J. F., “Single contacts and multiple encounters”, *Journal of Applied Physics*, v. 32, pp. 1420, 1961.

[15] LLANEZA, V., BELZUNCE F. J., “Study of the effects produced by shot peening on the surface of quenched and tempered steels: roughness, residual stresses and work hardening”, *Applied Surface Science*, v. 356, pp. 475–485, 2015.

[16] ZHANG, J, LI, W, WANG, H, SONG, Q., *et al*., “A comparison of the effects of traditional shot peening and micro-shot peening on the scuffing resistance of carburized and quenched gear steel”, *Wear*, v. 368-369, pp. 253-257, 2016.

[17] PYZALLA, A, WANGA, L, WILDA, E., *et al*., “Changes in microstructure, texture and residual stresses on the surface of a rail resulting from friction and wear”, *Wear*, v. 251, pp. 901–907, 2001.

[18] KHANAFI-BENGHALEM, N., FELDER, E., LOUCIF, K., *et al*., “Plastic deformation of 25CrMo4 steel during wear: Effect of the temperature, the normal force, the sliding velocity and the structural state”, *Wear*, v. 268, pp. 23–40, 2010.

[19] CHATTOPADHYAY, C., SANGAL, S., MONDAL, K., *et al*., “Improved wear resistance of medium carbon micro alloyed bainitic steels”, *Wear*, v. 289, pp. 168–179, 2012.

[20] LORENZO-MARTIN, C., AJAYI, O. O., “Rapid surface hardening and enhanced tribological performance of 4140 steel by friction stir processing”, *Wear*, v. 332-333, pp. 962–970, 2015.

[21] SUH, N. P., “An overview of the delamination theory of wear”, *Wear*, v. 44, pp.1–16, 1977.

[22] KANCHANOMAI, C, SAENGWICHIAN, B, MANONUKUL, A. “Delamination wear of metal injection moulded 316L stainless steel”, *Wear*, v. 267, pp. 1665–1672, 2009.

[23] MAHATO, A, YEUNG, H, GUO, Y., *et al*., “Sinuous flow and folding in metals: Implications for delamination wear and surface phenomena in sliding and cutting”, *Wear*, v. 376-377, pp. 1534–1541, 2017.

[24] SANCHEZ-SANTANA, U., RUBIO-GONZALEZ, C., GOMEZ-ROSAS, G., *et al*., “Wear and friction of 6061-T6 aluminum alloy treated by laser shock processing”, *Wear*, v. 260, pp. 847–854, 2006.

ORCID

Italo do Valle Tomaz	https://orcid.org/0000-0003-0441-9477
Mateus Campos Martins	https://orcid.org/0000-0002-0997-9070
Hector Reynaldo Meneses Costa	https://orcid.org/0000-0002-0887-6838
Ivan Napoleão Bastos	https://orcid.org/0000-0001-7611-300X
Maria Cindra Fonseca	https://orcid.org/0000-0001-9584-8394