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# EFFECT OF HEAT TREATMENT AND LOADING ON TRIBOLOGIC BEHAVIOR OF WELDING DEPOSITS FOR HARDFACING[1]

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## Abstract

This paper analyzes the effects of post welding heat treatment and applied load in wear tests on the tribological response of hard weld surfacing. The deposit was a martensitic steel obtained with a FCAW metal-cored wire under gas shielding of Ar-2%$CO_2$ and 2 kJ/mm of heat input. Cross sections were obtained from the welded coupon and subjected at 550°C during 2 hours. These samples, together with the as welded specimens, constituted the system under study. Cross sections were also extracted for both conditions to determine chemical composition, microstructure characterization, micro-hardness measurements in addition to friction and metal-metal wear tests in pure sliding at 500, 1250 and 2000 N of applied load. A microstructure composed of martensite and retained austenite was observed for both conditions. The as welded sample presented 16% of retained austenite whereas the heat treated one 8%. Heat treated coupons showed secondary hardening associated with precipitation phenomena. In the specimens tested at 500 and 1250 N the wear mechanism was oxidative and the as welded specimens presented higher wear resistance and a higher friction coefficient. Regarding the tested samples at 2000 N, wearing mechanism was delamination and heat treated samples resulted more resistant with a higher friction coefficient.

**Key words:** Hardfacing welding; Heat treatment; Friction; Wear; Martensitic steels.

## EFEITO DO TRATAMENTO TÉRMICO E DA CARGA APLICADA SOBRE O COMPORTAMENTO TRIBOLÓGICO DE DEPÓSITOS DE SOLDAGEM PARA RECOBRIMENTOS DUROS

## Resumo

Neste trabalho foram analisados os efeitos do tratamento térmico pós-soldagem e da carga aplicada no teste de desgaste sobre o comportamento tribológico dos depósitos de solda. O metal depositado foi um aço martensítico, obtido usando um arame tubular "metal-cored" pelo processo de soldagem semi-automática sob proteção gasosa de Ar-2%$CO_2$ com 2 kJ/mm de calor aportado. Do corpo de prova soldado foram extraídas amostras por cortes transversais aos cordões que foram submetidos a tratamento térmico de 550 º C por 2 horas. Estas amostras, junto com uma sem tratamento térmico (como soldada), foram as estudadas. A determinação da composição química, a caracterização microestrutural, as medições de dureza e testes de fricção e desgaste metal-metal em condição de deslizamento puro com 500, 1250 e 2000 N de carga aplicada foram realizados para as ambas condições. Para os dois casos, a microestrutura era constituída por martensita e austenita retida. A amostra como soldada apresentou um teor de austenida retida de 16 % e a tratada termicamente de 8%. As amostras tratadas termicamente apresentaram endurecimento secundário associado com eventos de precipitação. Encontrou-se que, para os corpos de prova testados entre 500 e 1250 N de carga, o mecanismo de desgaste foi oxidativo e que as amostras sem tratamento térmico apresentaram melhor resistência ao desgaste e maior coeficiente de fricção. Para os espécimes testados com 2000 N de carga, o mecanismo de desgaste foi delaminação e as amostras tratadas apresentaram melhor resistência ao desgaste e maior coeficiente de fricção.

**Palavras-chave:** Recobrimentos por soldagem; Tratamento térmico; Fricção; Desgaste; Aços martensíticos.

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## 1 INTRODUCTION

The technology of materials has experienced significant progress over the last years, especially in terms of surface coatings, with currently available specific coatings applicable to particular purposes and resistant to different types of demands. In this aspect, the systematic study of consumables and welding processes applied to hard surfacing is of great interest for the optimization of consumables design and for the assessment and tuning of welding procedures. Within this context, heat input, gas shielding composition, pre-heating temperature and post-welding heat treatment are some of the most relevant variables of the welding process.(1)

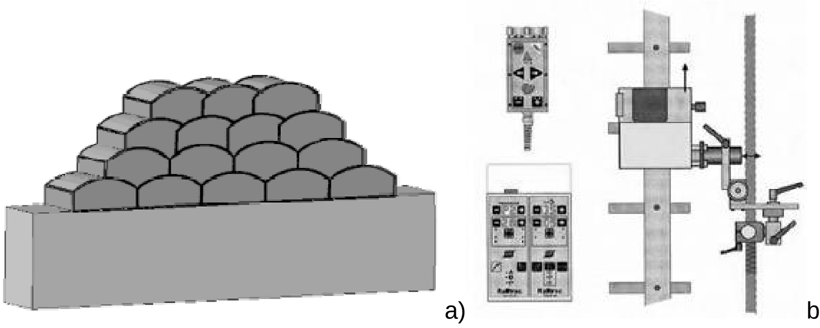
In recent years, tubular wires have been one of the most used options among the electric arc welding consumables. These consumables are highly productive and flexible for manufacturing of alloy grading, therefore constituting an economical alternative for big productions.(2) Metal-cored wires constitute state-of-the-art consumables with the advantage of a very low slag generation, fume formation reduction and higher deposition rate.(3,4) However, the information available on systematic studies of these types of consumables, especially for reclaiming applications is very poor.

Generally the material for wear-resistant applications presents a structure that is very hard or can be made hard by mechanical working or heat treatment; e.g. martensite or a soft matrix with hard particles (carbides or borides) according to the intended application.(5) Particularly, for metal-metal sliding or rolling service, where wear is mainly caused by sub-surface fatigue and adhesion, the materials usually used contain carbon from 0.1 to 0.7% and up to 20% alloying (Cr, Mn, Mo, W and/or V) such as martensitic tool steel or stainless martensitic steel.(1,6) These welding deposits often require a post weld heat treatment (PWHT). This kind of treatment adjusts final mechanical properties and allows relief of tensions, which are of great importance for the component useful life.(7) Particularly, the chosen alloy for this work was an appropriate one for hot work tools, such as forging dies.

The purpose of this work was to study the effects of both post weld heat treatment and the applied load in the wear test on tribological behavior and microstructural evolution of a martensitic steel weld metal obtained with a metal-cored tubular wire welded with gas shielded semi-automatic welding process, in order to better understand the relationships between process variables, microstructural evolution and properties.

## 2 MATERIALS AND METHODS

A test coupon consisting in a 375 x 75 mm AISI 1010 carbon steel plate, 19 mm thick, was surfaced by welding. Four layers were deposited with 5, 4, 4 and 3 beads per layer according to the sequence shown in Figure 1a.



a) b)

**Figure 1**. a) Welding sequence, b) Railtrac FW1000 System

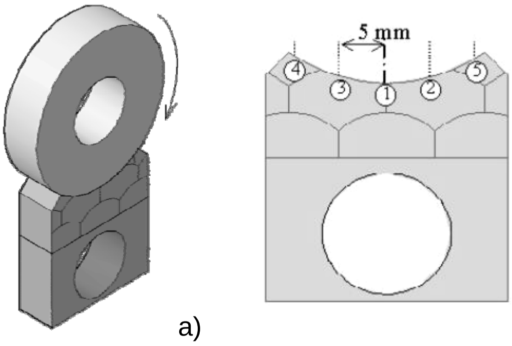
The consumable used was a 1.2 mm-diameter metal-cored tubular wire depositing a martensitic tool steel. A welding power source for pulsed semi-automatic arc welding Esab LAI 400P was used with the Railtrac FW1000 Flexi Weaver System as indicated in figure 1b. Welding parameters used are shown in table 1.

**Table 1.** Welding parameter

| **Shielding gas** | **Voltage [V]** | **Current [A]** | **Welding speed [mm/s]** | **Heat input [kJ/mm]** |
|---|---|---|---|---|
| $Ar\text{-}2\%CO_2$ | 28 | 180 | 2.6 | 1.9 |

The wire stickout was 20 mm and the gas flow was 20 L/min. Welding was done in the flat position with pre-heating temperature of 150°C. The quality of the welded coupon was evaluated by radiographic testing (RXT).

Twelve 10 mm-thick cross sections were obtained from the welded coupon; six of them were subjected to post-weld heat treatment at 550°C for 2 hours. This temperature was selected based on previous work.$^{(8)}$



a) b)

**Figure 2.** a) Arrangement of the wear pair specimens, b) Location of hardness measurements.

The chemical composition was determined on the last bead by Optical Emission Spectroscopy (OES) and local composition was determined by Energy dispersive X-ray spectroscopy (EDS) at different distances from the top surface, since composition is modified due to dilution with the base metal (AISI 1010). The analyzed conditions were characterized by light microscopy (LM) and X-ray diffraction (XRD). From XRD patterns, the retained austenite fraction was estimated by means of the direct peak comparison method [9]. From the heat-treated and "as welded" (AW) samples, specimens were milled for tribological testing. Testing was conducted with an AMSLER machine in conditions of pure sliding with loads of 500, 1250 and 2000 N. The sample geometry is shown in Figure 2a. AISI 1020 steel was used as a reference material. Before the tests, the samples were ultrasonically cleaned and weighed in an analytical balance. Hardness (HV1) was measured for each condition on the worn surface, as indicated in figure 2b. Furthermore, a hardness profile was also obtained from the surface up to a depth of 1200 μm.

Surface roughness was measured by means of a Hommelwerke T-1000 roughness tester. Measurements were made on the surface of the wear tested samples with different conditions of load (500, 1250 and 2000 N). Obtained results corresponded to average roughness (Ra) over a measured length of 4.8 mm.

Wearing behavior was studied in terms of the distance travelled by the wheel sliding on the plate; loss of weight was determined for 75, 550, 825, 1100, 1375, 1650, 3300 and 4950 m of travel distance. The friction coefficient was also measured for all loading conditions. Two sets (sample-wheel) were tested for each condition and the results averaged. The debris produced was collected in each case. Temperature was measured after one hour of continuous testing using a thermocouple located 1 mm far from the contact area between both surfaces. Finally, worn surfaces and cross sections were observed by means of light and electron microscopy to determine the wear mechanisms involved.

## 3 RESULTS AND DISCUSSION

### 3.1 Macrostructure Characterization

Figure 3a shows the welded coupon and Figure 3b a cross section of the welded specimen where the base metal, weld deposit (hardfacing) and absence of macroscopic defects (pores, slag inclusions, cracks, etc.) can be observed. These data were confirmed by RXT.

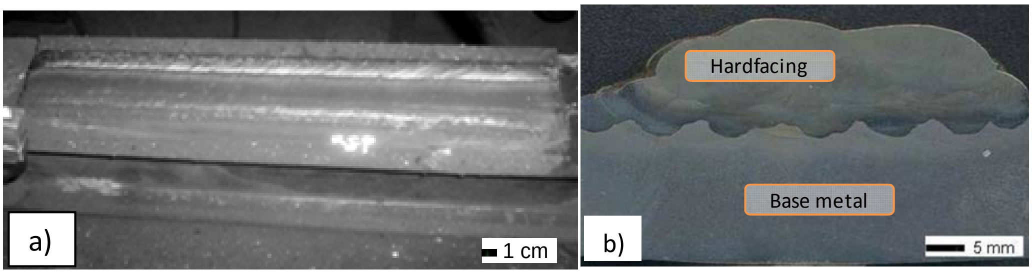


**Figure 3**. a) Welded coupon, b) Transversal sections of welded coupon.

### 3.2 Chemical Composition

Table 2 shows the results of chemical composition as measured on the surface of the last bead by means of spark emission spectrometry. Results complied with the manufacturer’s specifications.

**Table 2**. All weld metal chemical composition (% in weight)

| C | Mn | Si | Cr | Mo | V | W |
|---|---|---|---|---|---|---|
| 0.48 | 1.30 | 0.67 | 5.5 | 2.5 | 0.4 | 1.9 |

It is seen that the deposit corresponds to a Cr-Mo-V-W alloy, similar to the AISI H13 steel.

### 3.3 Microstructure

The microstructure for the as welded condition (figure 4a) was mainly composed by martensite (M) with some retained austenite ($\gamma$), with a denditric segregation pattern; these observations were consistent with what was expected for this type of materials.(7,10,11) In addition, given the increase of alloy content detected in the interdenditric area,(10) the martensitic transformation start temperature was locally reduced appearing retained austenite in the segregated regions [5]. On the other hand, and due to the fact that the deposit was welded in multi-passes, precipitation of small carbides was produced.(11).

Post weld heat treatment caused carbide precipitation and transformation of retained austenite into tempered martensite. The content of retained austenite was reduced from 16% to 8%. This can be corroborated in figures 4a and 4b. In previous works, the authors identified carbides of the type $M_{23}C_7$, $M_7C_3$, $M_2C$ and MC.(12)

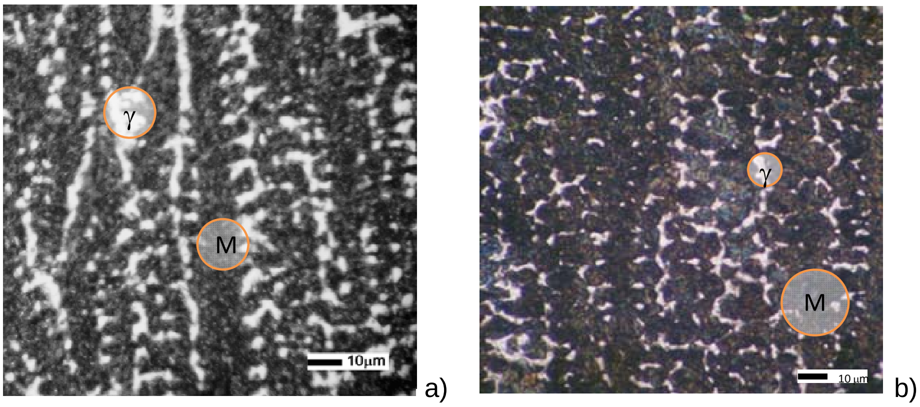
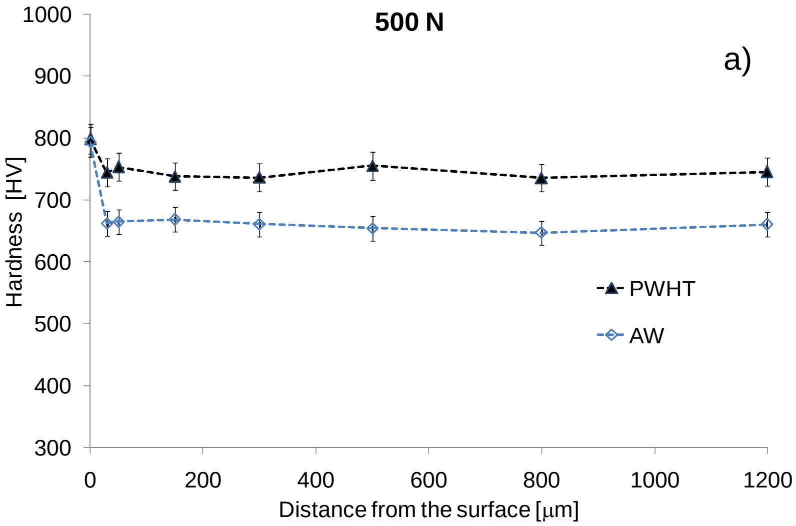


**Figure 4.** Microstructures of samples a) As welded b) Tempered at 550ºC.

### 3.4 Hardness

Hardness of the as welded and heat treated specimens were 640 HV and 740 HV respectively. The hardness increase with heat treatment was caused by coherent carbide precipitation which generated secondary hardening. Figures 5a, 5b and 5c show the hardness variation vs. the distance from the worn surface, for the AW and PWHT coupons, after testing with different loads.



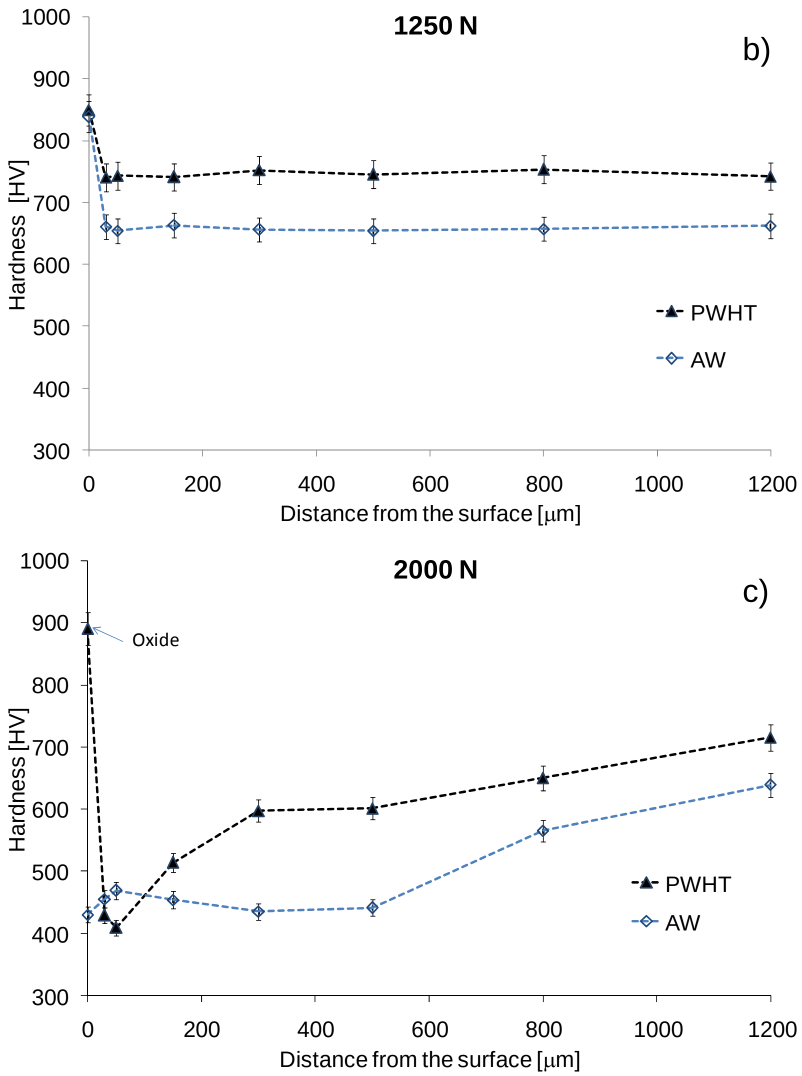


**Figure 5.** Hardness for tested sample at a) 500 N b) 1250 N and c) 2000 N

Figures 5a and 5b show martensite hardening near the worn surface caused by plastic deformation. The temperature reached, between 100 to 400°C, favored deformation and hardening.(13) The observed hardening increased with the load applied during the test. Hardening of the surface was similar for both conditions (AW and PWHT). This hardened microstructure, additionally acted as support or base for oxide layer formation. Furthermore it was observed that the zone affected by wear test was around 50 microns of depth from the surface.

The samples tested at 2000 N (Figure 5c), experienced a microstructure tempering caused by the temperature reached, which was 520ºC at 1 mm from the contact area. It was also observed that on the surface of heat treated specimens hardness was 896 HV and corresponded to the oxide formed on the surface.(14,15) The formation of this oxide layer was a result of both the high initial hardness microstructure which served as base or support and the temperature generated by friction.(16) The zone affected by the wear test was around 1200 microns of depth from the surface.

### 3.5 Wear

The wear rate was calculated from experimental results in terms of weight loss over the travelled distance. Figure 6 contains the results obtained for each condition.

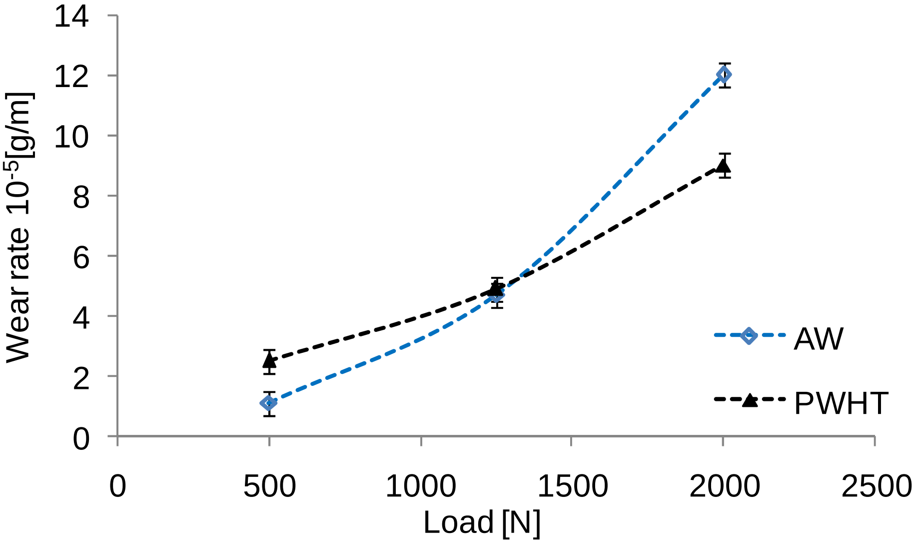


**Figure 6.** Wear rate for all tested samples.

Samples tested at 500 N showed that the AW coupons were more resistant to wear than the PWHT samples. This might be associated with the fact that during heat treatment the chromium in solution precipitated forming carbides and therefore reducing resistance to matrix oxidization.(17,18) Isolated oxide islands were found in worn surfaces of these samples, as can be seen in Figure 7a. Figure 7b shows EDS performed on zone A (oxide presence was confirmed by the EDS study). Abrasion lines, with orientation parallel to the sliding direction, were seen on the worn surfaces. These lines were produced by the rubbing of hard zones of the wheel during sliding.(19-21) The predominant wear mechanism was mild oxidative, promoted by the test conditions (low load and low speed); the oxidation resistance of the material could have controlled the wear rate being hardness not determinant.(12)

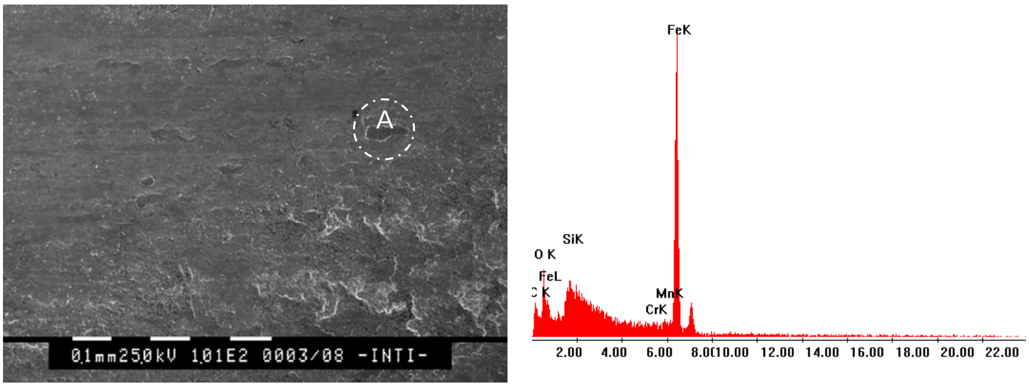


**Figure 7.** a) Top view of worn surface of sample AW tested at 500 N. b) EDS of zone A.

Samples tested at 2000 N showed that the PWHT coupons had better resistance to wear than AW ones. This was likely related to the higher plastic deformation substrate in AW samples, therefore producing a larger number of surface cracks parallel to the sliding direction (Figure 8a) which propagated until reaching critical length and coming off as debris material afterwards.(22-24) In turn, the material with the harder substrate allowed the formation of an oxide layer that rendered improved resistance to wear; see Figure 8b.(22,25)

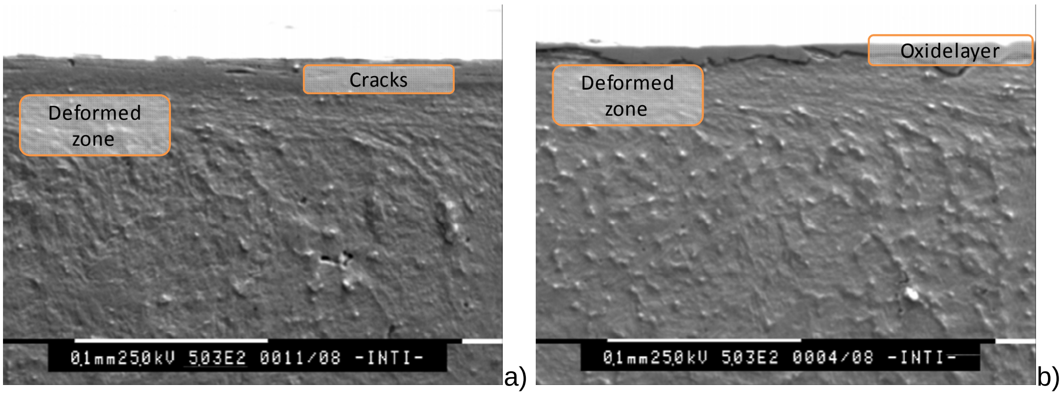


**Figure 8.** SEM images of the tested samples at 2000 N and a) AW b) PWHT.

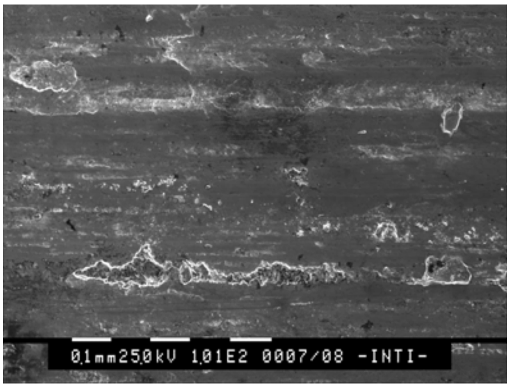


**Figure 9.** Top view of worn surface of sample PWHT tested at 2000 N.

XRD was performed on the worn surface to identify the oxides formed during the wear process. It was observed that retained austenite on the surface was fully transformed and also that oxides of the $Fe_2O_3$ and $Fe_3O_4$ types partially covered the worn surface (Figure 9); both factors improving wear resistance.(20) The predominant wear mechanism was severe oxidative.

The tested coupons at 1250 N were found in a transition situation where both wear mechanisms, mild oxidative and severe oxidative, exerted their influence.

### 3.6 Friction

The friction coefficient for all tested samples was found to vary between 0.3 and 0.4. Figure 10 shows that on coupons tested at 500 N and 1250 N with oxidative wear mechanism, samples with higher oxidation were those presenting lower friction coefficients, and, as previously discussed, were the most heavily worn. This might be related to the fact that with a larger surface covered by oxides, metal contact would be reduced and therefore lower the sliding force and friction.

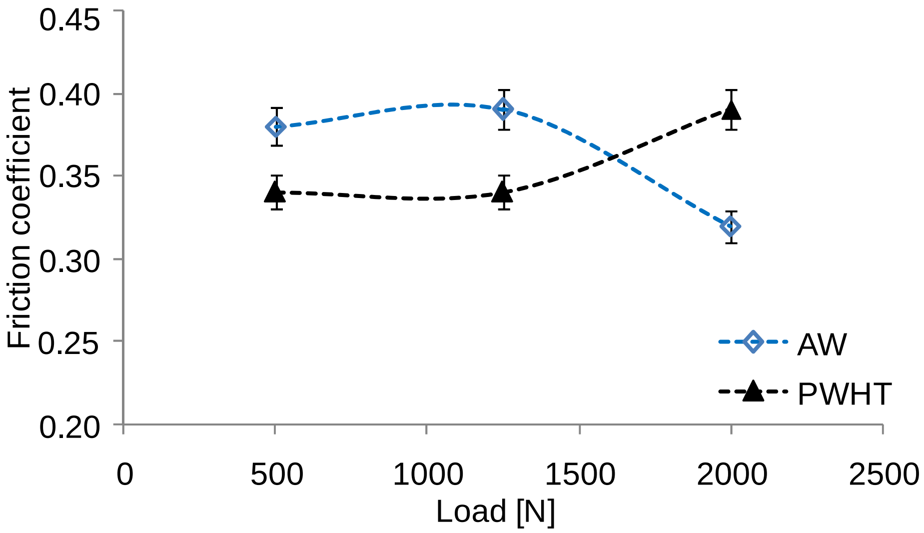


**Figure 10.** Friction coefficient for all samples.

When the applied load was increased to 2000 N, wear turned into delamination or severe oxidation and the friction coefficient was lower for the as welded condition. This might be related to the type and thickness of the oxide formed on the surface,(25) which might act as lubricant and reduce the friction coefficient. As all the worn coupons were covered with oxide, the loosening of the oxide layer might contribute to the mentioned lubrication effect, as previously shown by So and Munther.(25,26)

Figure 11 shows the accumulated oxide before entering the contact surface between the two pieces. Under certain size and hardness oxide conditions, part of this oxide entered the contact area and produced an abrasive effect increasing locally the friction coefficient.(27)

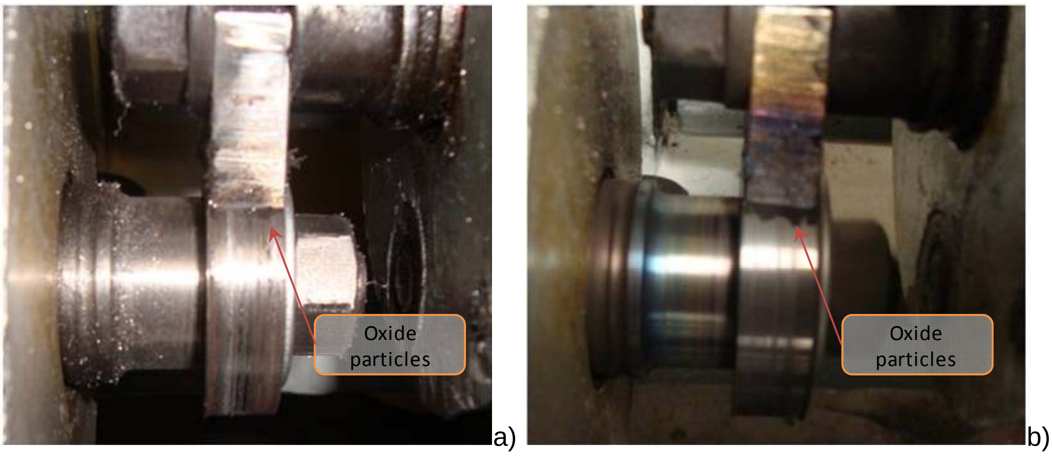


**Figure 11.** Images taken during the friction test at a) 500 N and b) 2000 N.

### 3.7 Roughness

Roughness of mechanized specimens surface was 0.8 μm. After the wear tests, roughness evolved according to the applied load as indicated in Figure 12.

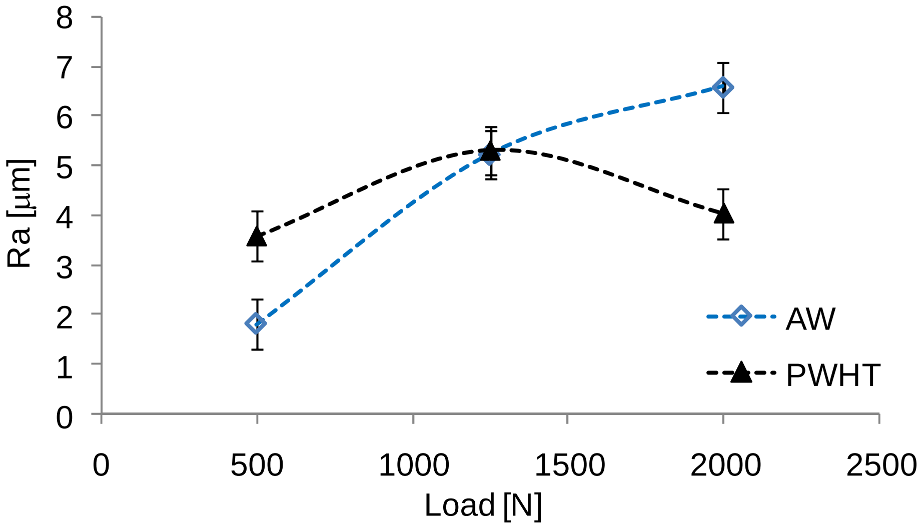


**Figure 12.** Roughness on surfaces of the tested coupons.

AW samples presented less roughness at 500 N and 1250 N loads. This might be linked to a less severe wear condition in these samples due to their improved resistance to oxidation (higher chromium in solution) resulting in reduced damage. On the other hand, in samples tested with 2000 N load, heat treatment favored the formation of a continuous oxide layer which helped the development of an improved resistance to wear and less roughness.(28)

## 4 CONCLUSIONS

For all conditions the microstructure was composed mainly of martensite with some retained austenite, with a denditric segregation pattern. The samples treated at 550ºC showed a secondary hardening effect accompanied by the transformation of retained austenite into martensite which resulted in an increase in hardness when compared to the as welded samples. The specimens tested at 500 and 1250 N of applied load showed hardening in the sub-surface region. Coupons tested at 2000 N experienced softening in this region due to the microstructure tempering caused by the high temperature. The heat treated sample resulted in the formation of an oxide layer with a hardness of 896 HV.

Wear of specimens in pure sliding conditions by AMSLER testing at loads of 500, 1250 and 2000 N showed a linear relationship between the weight loss and the travelled distance. Oxidation and plastic distortion was visible in cross sections of the tested samples. Wear mechanism was mild oxidative for samples tested at low loads. AW coupons presented improved resistance to wear and higher friction coefficient. At higher loads, deformation resistance of the substrate was determinant for wear. Mechanism was severe oxidative. Heat-treated samples presented higher resistance to wear and higher friction coefficient. Roughness as a function of the applied load was always lower in the less worn samples.

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