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Influence of microstructure on tribologically mixed layers

W. Tuckart[a,*], L. Iurman[a], E. Forlerer[b]

[a] Departamento de Ingeniería - Universidad Nacional del Sur Avd. Alem 1253, 8000 Bahía Blanca, Argentina
[b] Departamento de Materiales, CNEA-CAC, Av. Gral. Paz 1499 (B1650KNA), San Martín, Pcia. Bs. As., Argentina

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ABSTRACT

The purpose of this study is to determine the influence of microstructure on the formation and mechanical stability of tribologically mixed layers acting as a wear reduction factor. To this purpose, AISI 420 steel specimens of different initial microstructure were subjected to annealing, quenching and tempering to 673 K and to quenching and tempering to 943 K under pure sliding conditions.

The wear level for each case was evaluated on the basis of the applied load levels and in relation to the morphological features of the underlying surface affected by wear. Also locally stressed field gradients were identified by means of microhardness profiles, which were then correlated with measurements of the resulting plastic subsurface deformations on the basis of the distance to the tribolayer.

On the basis of the results, the conditions of formation and mechanical stability, the relations between the mechanical properties of the initial microstructure and the needed level of stress due to the resulting plastic deformation for the tribological layer to act as factor of wear rate reduction were assessed and are herein discussed.

1. Introduction

Wear rate controls the transition from severe wear to mild wear, especially for non-lubricated systems and it is strongly related to the magnitude and distribution of local strains and with stress conditions variation within a small volume of the material in the subsurface area.

In the past, several researchers analyzed (particularly in Al alloys against ferrous alloys) the influence of mechanically mixed layers (or MML) produced during sliding process as the ones that result from plastic flow, debris oxidation, fragmentation, transfer, compactation, and mechanical mixing. Such layers can conduce to protective effect of the rubbing wear affected region, increasing the tribosystem resistance wear [1–5].

On the basis of the results of wear tests made on Al–SiC composite materials, Venkataraman and Sundararajan [6] concluded that for the formation of a tribo-layer it is essential to exceed a threshold of subsurface strain resulting from shear stresses whose magnitude depends upon the existing SiC particles concentration values.

The same authors in another research paper [7] with Al alloys and the Al-MMC concluded that bulk strength does not correlate with the wear and friction behaviour. Additionally, there exists a strong correlation between transition behaviour from mild to severe wear, and hardness, thickness and composition of MML. On the other hand, the removal of the MML or its non-formation is responsible for the severe wear regime.

From a low alloy steel study, Tarassov and Kolubaev [8] reported complex dependence between load and sliding speed with the coefficient of friction due to structural changes occurring in the specimens subsurface layers under the cooperative action of both temperature and deformation.

However, the effect of microstructure characteristics in iron alloy on the mechanical stability of tribologically mixed layers enabling the latter to act as a means of wear rate control has not been fully analyzed so far.

The purpose of this paper is to identify the influence of initial microstructure on the formation and stability of a tribologically mixed layer that may restrain the wear rate of the tribosystem. The accumulated gradients of damage resulting from subsurface plastic deformation are herein estimated by determining the stress fields accumulated by deformation. The attained results were correlated with those obtained from bulk wear and mechanical properties in order to discuss the effects of subsurface hardening on friction and wear tribolayer behaviour.

In this study, it has been experimentally demonstrated that for the tribological layer to act as wear-protective not only are necessary the conditions to enable its formation, but also the attainment of its mechanical stability.

* Corresponding author at: Engineering Department - Universidad Nacional del Sur Avd. Alem 1253, 1°, 8000 Bahía Blanca – R, Argentina. Tel.: +54 291 4595156; fax: +54 291 4595157.
E-mail address: wtuckart@uns.edu.ar (W. Tuckart).

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Table 1
Maximum contact stress in the initial time as a function of the normal load applied.

Applied load [N]	200	275	350	425	500
Maximum contact stress [MPa]	1638.4	1821.9	1974.5	2107.2	2225.4

2. Materials and methods

2.1. Material and equipment

For this purpose AISI 420 steel (wt%: 0.42 C%, 13.89 Cr%, 0.75 Mn%, 0.33 Si%, 0.0027 P%, 0.0098 S% and Fe balance) 40 mm diameter and 5 mm thick annular test samples were prepared.

Some of the samples were tested in such as-received microstructure conditions (named “Rec”), while others were austenized to 1303 K during 30 min followed by oil quenching. A number of specimens were tempered to 673 K for 45 min (T673). Still other samples were tempered to 943 K for 45 min (T943). For each case, counting of carbide size distribution in the initial microstructures was made using a Nikon NIS Elements D3.1 software.

Wear tests under pure sliding conditions (one sample mobile on a fixed one) with an Amsler wear machine using normal constant loads of 200, 275, 350, 425 and 500 N were carried out, at a temperature of 293 K and 40–50% ambient relative humidity. The initial contact stresses produced were calculated using the Hertz theory [9] and shown in Table 1 ($\upsilon = 0.3$ and $E = 200$ GPa) [10]. The relative speed between the probes with sliding contact was of 0.80 m/s, for a total of 15,000 rotations (equivalent to 1728 m of distance).

In this experimental work only the fixed specimen was analyzed as it was the one subjected to pure sliding conditions.

Quantitative wear by the weight difference technique with a scale of 10^{-4} grf sensibility was used and the debris produced during the tests were collected every 216 m of sliding distance (5 min) and weighed after the test. Although the debris came from both specimens, for the most part they correspond to fixed specimen, mainly during the running-in stage due to change in the geometry contact – noconforming to conforming.

The triboxides phases were identified by X-rays diffractometry (XRD) by means of a RIGAKU Denkid, model max IIIC equipment, between $2\theta = 20$–90 with a Cu K$\alpha = 1$, 5405 Å with a conventional $\theta/2\theta$ Bragg–Brentano symmetric geometry. Rietveld method by means of MDI Jade software was used to analyze the X-rays diffraction patterns.

During the tests, friction torque and temperature in the specimen near the contact zone were registered and fed into computer via interface as functions of time (60 sample by min); specifically, temperature was measured by a chromel–alumel 1 mm diameter thermocouple inserted into the fixed probe ~1 mm below the sliding surface as shown in Fig. 1. After the test, the width of the wear scar was measured to determine the final contact stresses as indicated in Fig. 1.

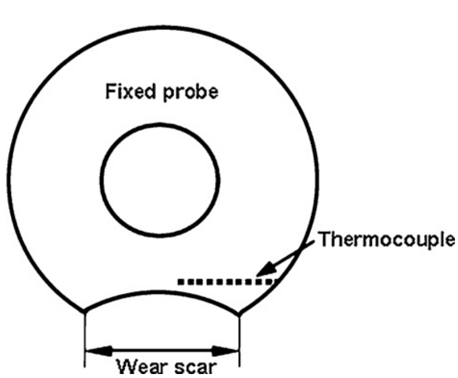

Fig. 1. Reference pattern of the wear scar and thermocouple disposition in fixed probe during the testing.

The tribosurface and subsurface were analyzed by optical microscopy (OM) and the bulk by scanning electronic microscope (SEM) on Philips XL30, with secondary electrons detector.

The mechanical characterization of the bulk was made with Vickers hardness and the microstructure was studied by optical microscopy and 0.020 and 0.040 kgf Vickers microhardness tests.

The metallographic sections were begun by cutting cross-sectional to the tribosurface and the lateral side ground manually using 2000 grit abrasive paper and finally polished with 0.5 μm Al_2O_3 water-based slurries. For optical microscopy ‘Marble’ reagent (100 ml H_2O, 100 ml hydrochloric acid and 20 g copper sulphate) was used.

2.2. Estimate of subsurface stress fields

By applying the model proposed by Nobre et al. [11] and using Vickers microhardness profiles, local stress fields were estimated. This method linearly relates the increase in hardness with the field of stresses that may be estimated for every level of plastic deformation in terms of hardness using the following equation:

$$\sigma = \sigma_{EH}\left(\frac{1+\gamma\Delta H}{H_0}\right)$$

where σ is the local stress, σ_{EH} is the substrate elastic limit, γ is a dimensionless constant, ΔH is the relative hardness variation and H_0 the substrate hardness. According to Nobre [11], the value of γ is 2.8 when microhardness values are used for the calculations.

Because this model ignores possible microstructurals changes like phase transformations caused by heating friction, it was applied only on samples in which the metallographic subsurface studies did not show evidence of transformation in the tribolayer/bulk interface region.

3. Results

3.1. Microstructural characterization

Fig. 2 shows the samples microstructures with one aspect in common: in all them a fine distribution of particles (FeCrC carbides precipitation) presenting different shapes can be observed; namely, rounded, globular whereas others are elongated and bigger, localised either in grain boundaries for Rec samples or in grain boundaries of the previous austenite for the T673 and T943 microstructure. The Rec sample with ferritic matrix posses a 245 ± 3 HV_{10} microstructure hardness, while both T673 (attained 542 HV_{10}) and T943 (attained 322 HV_{10} hardness level) have martensitic matrix due to quenching and tempering heat treatment.

This is in coincidence with a part of the PhD dissertation realized by Tuckart [12], carried out in AISI 420 with the same austenised and quenched conditions and analyzed using carbon thin foils in transmission electron microscopy (TEM), from which it was observed that the precipitate carbides present from martensite microstructures (T673 and T943) are bigger than those of the annealing condition. The sizes distribution is dependent on austenizing temperature [13].