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Influence of sliding direction changes, contact frequency and Bauschinger effect on the wear of dual phase steels

M. Ruiz-Andres, A. Conde, J. De Damborenea, I. Garcia*

Department of Surface engineering, Corrosion and Durability, National Center for Metallurgical Research (CENIM-CSIC), Avda. Gregorio del Amo 8, 28040 Madrid, Spain

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ABSTRACT

Friction and wear rate behaviour of dual phase steel discs (DP600) have been studied as a function of sliding speed (0.5–1.25 m/s) and contact frequency (3.5–8.5 Hz) under unidirectional and bidirectional (reversal motion) ball-on-disc dry sliding wear tests. The wear rate is found to be higher under unidirectional sliding. The Bauschinger effect – BE-appears to take place during the bidirectional sliding processes. However, it is only evident when the sliding direction is reversed for some limited times, where the mass loss decreases accompanied a weakened strain-hardening effect. Moreover, the BE in the DP600 steel discs is also affected by both the sliding speed and the contact frequency, but its effect is clearly different.

1. Introduction

In relation to the machining processes of new hard materials, Tang et al. [1,2] recently addressed the question concerning whether it is more efficient to perform machining/grinding under unidirectional or under bidirectional (forth-and-back) sliding conditions. Their results on specimens of Cu–Zn alloys, tested against steel, in a modified wheel abrasion tester, showed that there is a remarkable difference in the wear rate. They reported that reversing the sliding direction decreases the wear damage. They thus concluded that unidirectional sliding could be more effective than bidirectional when used for machining or grinding materials. This result was attributed to the Bauschinger effect (BE) that can take place on the Cu–Zn alloy.

The BE is generally defined as the phenomenon whereby the flow stress applied to plastically deform a material, in the reverse direction, is lower than that in the original direction [3], i.e. the BE is characterised by a decrease in yield strength after a change in the load path [4].

In metals, the BE primarily results from the directionality of the mobile dislocations in their resistance to motion [5], and their annihilation when new dislocations with opposite sign are generated by reversed applied stress. This annihilation leads to a reduction in the strain energy and is, therefore, a favourable energy process [6]. Both the reversible movement of dislocations and their annihilation can derive in softening during stress reversal.

Consequently, the BE clearly affects any plastic deformation when materials are subjected to cyclic back and forth strain path and/or to variations in the applied load [4]. At macroscopic scale, many mechanical processes are associated with the BE. For instance, most of the operations related to metal forming which, in turn, involve reverse strain cycles, such as plate fabrication or pipeline-making processes [7]. Hence, this information is of significant importance for the enhancement of machining or grinding processes with higher efficiency and their associated energy consumption via the work direction. Moreover, it may be helpful to control the wear damage in a component which is in constant dynamic contact with others [6]. At microscopic scale, components such as microelectromechanical devices (MEMS) also show BE [4].

In LiF single crystals, Harea et al. [8] found that the wear is higher under unidirectional sliding. The authors concluded that these results are related to the BE and also, to a redistribution of the contact spot as a result of the ploughing and adhesion of debris to the interacting surfaces.

On the other hand, Wu et al. [9] studied the wear behaviour and tribocorrosion of TiN coatings sliding against corundum in two different wear tests, namely ball-on-disc (unidirectional sliding) and ball-on-plate (reciprocating motion) where both were performed in air and water at a constant applied load. Results showed that the TiN wear rate is higher under bidirectional sliding than in unidirectional tests. These results do contravene the aforementioned results on Cu–Zn alloys.

* Corresponding author. Tel.: +34915538900; fax: +34915347425.
E-mail address: i.garcia@cenim.csic.es (I. Garcia).

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To the author's best knowledge, no other works have reported on the responses of other materials after a changeable wear sliding direction or path. In the present work, the authors attempt, therefore, to elucidate whether such BE is noticeable on the wear of steels, namely dual phase (DP) steels. In the classic delamination theory of wear proposed by Suh in the 70's [10,11] and extended by other authors [12,13] plastic deformation of the sub-surface region is accumulated with repeated loading until cracks are nucleated below the surface. Once cracks nucleate further loading and deformation promotes crack growth running parallel to the surface until finally thin wear sheets delaminate. The sub-surface stress due to the accumulation of plastic shear strain was studied extensively by several authors [14,15] and detailed models for stress components values and stress accumulation in function of several parameters have been described. Moreover, cracks propagate in a region below and behind the contact where material is elastic and stress is tensile and therefore subjected to successive cycles of compression and tension [13]. However, all such models assumed unidirectional sliding for the calculation of plastic work, stress and work hardening.

Several authors [3,16,17] studied the BE in DP steels during tension–compression tests. It has been reported that the BE and permanent softening are observed in these materials. Thus, it is expected that the BE is perceivable in these steels (DP) when they are subjected to several sliding direction reversals during testing.

In addition to the rotation direction condition, there is still a need to develop a more comprehensive understanding of friction and wear behaviour if the disc – studied material – is exposed to a full wear characterisation.

When performing wear tests using a pin/ball-on-disc configuration, the pin/ball is under continuous contact with the disc, and consequently, as the contact load and the sliding speed are considered the controlling operational wear parameters which best define the wear test conditions for a wide range of materials, the pin material would therefore become completely characterised. However, when the aim is the characterisation of the disc material, its wear rate or wear mechanism, the contact varies since the disc and the ball are not equivalent in pin/ball-on-disc wear tests.

Garcia et al. [18], derived from Quinn's mild oxidative model [19–21], developed a novel approach to sliding ball-on-disc wear tests considering that, from the viewpoint of the disc, each part of the wear track is in discontinuous contact with the counterbody. The authors found that the contact frequency, defined by the rotation frequency of the disc, became the most influencing parameter on the wear rate of TiN coated steel discs when tested in a pin/ball-on disc configuration. The role of the contact frequency was also later confirmed in ball-on-disc wear tests on tool carbon steel [22] and dual phase steel [23] discs sliding against corundum. The need to consider the contact frequency on tribocorrosion systems has also been pointed out in recent mathematical models for sliding wear in both gaseous and aqueous environments [24]. In nuclear pressurised water reactors (PWR), some tubular components wear damaged have been found to be sensitive to activation or latency time (the inverse of the contact frequency) as a result of vibrating contacts [25].

It would therefore be interesting to evaluate the role which the operational wear parameters independently play, namely sliding speed and contact frequency, on ball-on-disc tests operating under unidirectional or reversed sliding wear directions.

The present work thus focuses on how the sliding direction (i.e. uni- and continuously reversed bidirectional sliding), and the operational wear parameters (i.e. sliding speed and rotation frequency) affect wear, the BE, and the strain-hardening rate under discontinuous sliding contact conditions. In this sense, the wear tests were conducted on high strength DP steel disc materials sliding against corundum balls.

2. Experimental

A commercial high strength low carbon dual phase steel, namely DP600, was used in this work. The chemical composition of this DP600 steel is given in Table 1. The as-received material was an industrially processed, cold-rolled sheet with a hardness of 230 ± 5 $HV_{1\ kgf}$ and a thickness of 1.5 mm. Subsequently, this sheet was machined into discs with an outer diameter of 120 mm. The average surface roughness of the steel specimen is 0.386 μm (R_a) approximately. High purity (99.9%) corundum balls with 3 mm of diameter and surface roughness of 12.83 nm (R_a) were selected as counterbody due to their high wear resistance and chemical inertness.

Tribological characterisation was conducted using a ball-on-disc UMT-2-Bruker tribometer. In this configuration, the corundum ball was loaded on top of the disc. This set-up facilitates the third body interactions since it limits the ejection of the debris from the contact area in comparison to other configuration where the disc is loaded on top of the pin/ball. Wear tests were carried out at a steady contact load of 2 N for total number of 2000 cycles. These tests were performed under ambient conditions without lubrication. The room temperature was 25 ± 2 °C and the relative humidity of the surrounding atmosphere was 40% RH, approximately. Previously to wear testing, all the specimens were degreased with suitable solvents and dried by blowing cold air on to them.

In order to assess the BE in the DP600 steel after wear processes, both unidirectional and bidirectional motion were compared by taking into account the cyclic number, CN, as proposed by Tang et al. [1]. Such CN indicates how often the rotation direction of the disc is reversed. The unidirectional sliding is thus represented by CN=0. Conversely, for bidirectional wear tests, namely $CN \neq 0$, the rotating direction was continuously varied after a fixed number of rotations as follows: CN=2, 5, 10, 20, and 50. In other words, CN=i (being $i > 0$) corresponds to i cycles which, in turn, are related to $i \times 2$ times of reversing the wear sliding direction during the total number of rotations, namely 2000. For instance, CN=20 represents 20 cycles corresponding to $20 \times 2 = 40$ times the rotation direction changes during the 2000 total number of the disc rotations.

Moreover, to independently study the effect of linear sliding speed, and/or rotation – or contact – frequency on the wear rate for the DP600 discs with reversed wear path, thoroughly designed experimental parameters were used. Notice that the sliding speed (linear speed), v, at a given contact frequency (angular speed), f, varies by adjusting the wear track diameter, D, in the case of pin-on-disc or ball-on-disc sliding tests. These three operational parameters are related as follows:

$$v = \pi \cdot f \cdot D \quad (1)$$

whereby, a series of ball-on-disc wear tests were conducted at a given constant sliding speed, but at different rotation speeds, by

Table 1
Chemical composition of DP600 dual phase steel (%wt).

	C	Si	Mn	Cr	Ni	Mo	Al	Nb	V	Fe
DP600	0.122	0.38	0.91	0.021	0.045	< 0.01	0.043	< 0.005	< 0.01	Balanced