Tribology International 90 (2015) 32–42

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Friction and wear behaviour of dual phase steels in discontinuous sliding contact conditions as a function of sliding speed and contact frequency

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ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form
27 March 2015
Accepted 29 March 2015
Available online 7 April 2015

Keywords:
Steel
Sliding wear
Contact frequency
Oxidative wear

ABSTRACT

Friction and wear rate behaviour of dual phase steel discs (DP600) as a function of sliding speed (0.05–3.75 m/s), and contact frequency (0.6–16.5 Hz) have been studied under unidirectional ball-on-disc dry sliding conditions. The coefficient of friction (COF) and wear rate exhibit not only a highly dependence on the sliding speed, but also on the contact frequency which appears to be the key factor determining the wear behaviour of the DP600 even at constant sliding speed. The wear mechanism is mainly oxidative. The validity of Garcia–Ramil–Celis model is demonstrated for discontinuous sliding contacts at contact frequencies below 7 Hz. However, above 7 Hz, the disc behaves as if it were subjected to a continuous sliding contact.

1. Introduction

Traditionally, normal contact load and sliding speed are considered the most important parameters in tribological systems. These parameters are commonly used to construct contact wear maps, which are a useful tool to predict the conditions under which a tribosystem can operate safely [1].

Wear maps have been experimentally and theoretically constructed for systems based on technological important materials, such as steel sliding versus steel [2], steel versus nitrided steel [3], and also aluminium alloys versus steel [1,4]. In those wear maps, a small variation in contact pressure, and/or in sliding speed, may result in a significant transition between the two distinct wear mechanisms.

Wear mechanism occurred in dry sliding tests have been classified in the literature [5–8] into different types. All these classifications are strongly related to the previous classifications proposed by Burwell et al. [5], with seven wear types, and Archard et al. [9], with only two. Tabor [7] just distinguished three types: adhesive, non-adhesive, and a mixture of both. The author discussed the nature of the atomic forces at the interface but also the way the interface deforms under the action of a pull-off force (for adhesion) or a tangential force (for sliding), and how the bond itself ruptures under shearing. Ludema [6] defined scuffing, namely the roughening of surfaces by plastic flow whether or not there is material loss or transfer. Whilst Quinn [8] established mild and severe wear as the two main mechanisms of wear.

Oxidative wear is a form of mild wear, one of the two basic classifications for non-lubricated sliding wear firstly proposed by Archard et al. [9]. While mild wear is characterised by oxidised wear debris generation and smooth oxidised wear surfaces. This type of wear clearly involves a reaction with the environment, in particular with oxygen [10]. Moreover, the oxidative wear mechanism occurs when sliding surfaces are subjected to thermal oxidation. The heat is externally provided with a heat source, or internally by the frictional heat produced in the sliding contact.

The mild oxidative wear model proposed by Quinn [10–14] for a tribosystem comprised by a pin sliding against a disc, takes place in two successive steps. Initially, the asperities on both surfaces the body (pin) and the counterbody (disc) oxidise as a consequence of a high local rise in temperature due to friction. The oxide layers formed at these asperities usually grow following a parabolic trend or linear growth law [15]. Then, when locally a critical oxide thickness is reached at the asperities, the oxide layer breaks off and a new oxide layer is generated on the freshly exposed metallic surface. Thus the expression for the volumetric wear loss in a pin, W, leads to as follows

$$W = \frac{d A_c \exp(-Q/RT_f)}{\xi^2 \rho^2 v} \frac{F}{H} L \qquad (1)$$

where d is the asperity contact area average diameter, A_c the oxidation activity factor, Q the Arrhenius activation energy for oxidation, R the

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http://dx.doi.org/10.1016/j.triboint.2015.03.038
0301-679X/

gas constant, T_f the local temperature at the asperity, F the normal load, L the sliding distance, ξ the critical oxide thickness, ρ the density for the material tested, v the sliding speed, and H the hardness for the material tested.

Once the oxide layer is broken off, the oxide particles formed from the layer may agglomerate to generate a protective layer establishing equilibrium between formation and delamination or fragmentation of the layer [16,17]. When performing wear tests using a pin/ball-on-disc configuration, the pin itself -or the 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 material of the pin would become fully characterised. However, when the aim is the characterisation of the wear rate or wear mechanism of the disc material the contact varies since the disc and the ball are not equivalent in a pin/ball-on-disc wear tests.

Garcia et al. [18] 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 discs sliding against corundum [19]. The need of considering contact frequency on tribocorrosion systems has been also pointed out in recent mathematical models for sliding wear in both gaseous and aqueous environments [20], In nuclear pressurised water reactors (PWR), some tubular components wear damage have been found to be also sensitive to the activation or latency time (inverse of the contact frequency) resulting from vibrating contacts [21].

Wear studies are found in almost all industrial sectors due to the relevance of a surface failure, which can negatively alter the performance of industrial facilities, shorten their service life and comprising safety issues [22]. Over the last decades, huge efforts have been made to develop materials of high wear properties to achieve optimal performance with maximised service life.

One of these new materials with improved properties is the microstructure-strengthened steel [23], namely DP steels. The unique combination of mechanical properties such as strength, ductility [24,25], toughness, good formability and excellent surface finish [26] makes them to one of the most important recent advances in high strength low alloy steels (HSLA).

Dual phase steels are considered as light steels with high strength [27], consisting of about 75–85% continuous ductile ferrite matrix phase with the remainder being mainly hardened martensite islands randomly distributed [28]. Moreover, they are known for being widely used in the automotive industry due to the need for improving fuel efficiency [29–31], with its subsequent energy saving and environmental protection [32].

Although some researchers [33–43] have worked on the tribological aspects of DP steels, there is still a need to develop a more comprehensive understanding of their friction and wear behaviour, taking into account the specific characteristic of the interaction of these steels in discontinuous sliding contacts.

The present work focuses on the role of the contact frequency as an operational wear parameter in ball-on-disc tests operating under dry sliding conditions. The wear tests were, conducted on high strength DP steel disc materials sliding against corundum balls. The friction behaviour and the wear evolution of these DP steel discs were carefully analysed at specific sliding speeds and rotation frequencies.

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$_{1\ \mathrm{kgf}}$ 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 its high wear resistance and its chemical inertness.

Tribological characterisation was conducted using a unidirectional 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 interaction 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 2000 total number of 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 independently study the effect of linear sliding speed, and/or rotation -or contact- frequency on the wear rate for the DP600 discs, a thorough design of the 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 to as follows:

$$v = \pi \cdot f \cdot D \qquad (2)$$

Whereby, series of ball-on-disc wear tests were conducted at a given constant sliding speed but at different rotation speeds by modifying the wear track diameter to adjust Eq. (2). In addition, series of ball-on-disc wear tests were carried out at a fixed rotation speed but at different sliding speeds, once again modifying the wear track diameter. In this sense, the sliding speed was varied between 0.1 and 3.75 m/s and the track diameter ranged within an interval from 12 to 75 mm. Thus the contact frequency studied in the present work varied between 0.6 and 16 Hz.

The volume wear loss of the disc was determined by optical confocal profilometer, Sensofar PLμ2300. The volume wear loss was calculated from the average of the cross-sectional area measured at four different locations along the wear track, and multiplied by the wear track length. The wear rate, as a function of the different experimental conditions, was obtained by dividing the volume wear loss per unit load and sliding distance.

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