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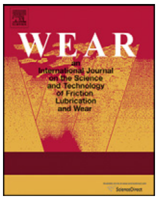

A wear model based on cumulative cyclic plastic straining

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ABSTRACT

Given the specific micro-structure of some steel grades, under tribological conditions the sub-surface material or sub-layers of sliding bodies are prone to cumulative cyclic plastic deformation, leading to the formation and emission of wear debris.

In the present paper, a new wear model based on a cyclic ratchetting-type plastic deformation of sub-surface material is proposed. It is considered that the debris is formed and the wear-loss occurs when the accumulated plastic deformation at sub-surface exceeds “a critical strain” or “rupture limit”. The model takes into account the number of cycles or test duration, a characteristic thickness of the sub-layer dependent on tribological conditions and material properties, the shear rupture ductility and an average plastic strain increment. The average plastic strain increment is estimated by numerical simulation of pin-on-disc friction. A very close correlation is found between the predicted and experimental wear heights versus time and/or versus the number of cycles.

The wear investigations were carried out on a high-temperature pin-on-disc tribometer under dry friction conditions. Experiments were performed under constant load, speed and disc temperature for different durations. The steel grade involved was a tempered martensitic tool steel X38CrMoV5 (AISI H11). Wear mechanisms were investigated by Scanning Electron Microscopy (SEM) observations in surface and cross-section.

1. Introduction

Hot metal forging tools used in processes such as forging, rolling or metal sheet forming, are subjected to transient thermal and mechanical loadings. Under these conditions, the contact surfaces of the tools are damaged by complex interactions between wear and thermal fatigue. In addition, the wear and thermal fatigue that are subjected to is coupled with oxidation. It is well known that the wear mechanisms of two bodies in relative movement depend on various parameters and conditions acting conjointly. The loading conditions (stress and speed) the surface and interface properties (dryness, lubrication, oxidation and asperities), the material behaviour (static and cyclic plastic behaviour) and the mechanical properties (flow stress and/or hardness, fatigue and rupture properties) are among the parameters required to investigate the quantitative evaluation of wear.

One of the characterization difficulties encountered here is that surfaces and sub-surfaces cannot be considered as simple laboratory specimens, where stresses and strains are straightforward, but rather as samples subjected to thermo-mechanical loading gradients and micro-structural modifications (Mechanical Mixed Layers for example), requiring appropriate simulations and thermo-mechanical analysis.

Knowledge of the local stress and strain distributions in the contact region is a key requirement to gain a better insight into the wear mechanisms and thus achieve an appropriate modelling of the wear. The changes in the contact features (e.g. asperity and sub-surface aspects) during the wear process constitute an additional difficulty since the boundary conditions are continuously evolving. Friction evolves during wear, mainly because of the evolution of the contact geometry and also because of the formation and circulation of debris. These complex and combined parameters make wear prediction difficult, in particular where a microscopic or “local” approach to friction and wear is concerned. The coupling effects of material properties and loadings need to be addressed.

Models may be found in the literature dealing with different tribological fields and wear mechanisms [1]. In many cases these are macroscopic and phenomenological approaches aiming to describe the microscopic wear mechanisms occurring at the contact regions. Archard’s wear law is one of these well-known quantitative macroscopic models [2]. This law and its modified versions [3–6], introduce a parameter K that is experimental conditions dependent and therefore needs to be adjusted or estimated for each application, in particular when the industrial applications, such as forming tools, are of concern.

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Other authors have found a considerable amount of microscopic evidence revealing that the surface layer close to the "friction surface", in particular in ductile materials, may be subjected to large plastic shearing under sliding. To develop wear models, several authors have used the plastic deformation concept of the surface and the gradient of plastic deformation inwards from the surface [7–18].

In delamination theory, the plastic deformation of the more ductile body is caused by the asperities of the harder body and induces a cyclic plastic shear strain that accumulates with repeated cycles.

A further important characteristic, even in sliding friction, involves non-proportional back and forth loading conditions and hydrostatic pressure [19].

The loading undergone by the counterparts in cyclic stressing is similar to that encountered in fatigue loading, but differs in several ways [14]. Firstly, the major deformation mode in friction corresponds to shear [12]. In friction, the shear strain can be much higher than the uni-axial tension ductility, whereas the deformation in compression (due to normal forces in tribological tests) is much lower, with strains of only 1–2%. Secondly, the loading under friction leads neither to constant deformation amplitude nor to constant stress amplitude. Moreover, an asymmetric loading in fatigue mode favours the ratchetting effect.

Furthermore, high hydrostatic pressure may increase ductility by eliminating or retarding the initiation and growth rate of damage [20,21]. The friction shear could be compared to torsion strain. So, it could be considered that the hydrostatic pressure could increase ductility and deformation accumulation before rupture by shearing.

Kapoor et al. have studied and are working on the ratchetting concept through a ratchetting failure-based approach to wear modelling, where ratchetting failure occurs when the accumulated deformation exceeds a critical value [11,16–18].

This contribution deals with a wear model based on sub-surface cyclic ratchetting plastic strain accumulations as the basic process of debris formation and rupture. It is considered that the debris is formed when the cumulative plastic deformation in sub-surface layers achieves a critical limit that is governed by the "ductile rupture property" of the material.

Based on experimental observations and detailed microscopic examinations, a material-dependent parameter is introduced to describe the physical wear mechanism that is observed. The model is assessed on a tempered martensitic tool steel, X38CrMoV5-AISI H11, examined on a high-temperature pin-on-disc tribological facility, used in hot metal forming.

In this investigation, attention is only focused on the role of the cyclic plastic strain of the hard material (X38CrMoV5, AISI H11) used as a pin. The role of the cyclic plastic strain behaviour of the more ductile steel (XC18-AISI 1018), used as a disc, is not addressed in this paper. In addition, in order to better disconnect the complex effects and interactions of a high-temperature friction test, it was decided to assess the friction and wear in the specific conditions of a steady-state temperature.

2. Experiments and materials

2.1. High-temperature pin-on-disc tribometer

The investigations were carried out on a high-temperature pin-on-disc tribometer under dry friction conditions. A detailed description of this tribometer is given in [22,23]. The disc is a cylinder of 30 mm diameter and the pin has a cylindrical shape (diameter 10 mm) with a truncated conic end with a flat circular surface of 2 mm diameter (surface contact) (Fig. 1).

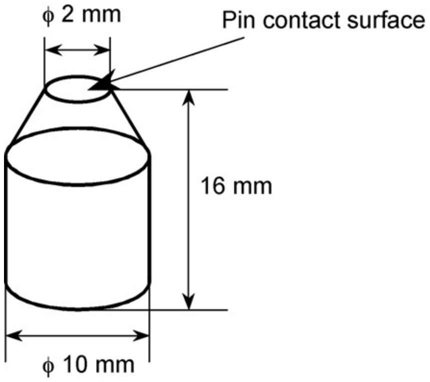

Fig. 1. Schema of the pin geometry (the conic angle is 45°).

The disc was heated by a high-frequency induction CELES facility (3 kW). The disc surface temperature was controlled by a bi-chromatic infrared pyrometer. First the disc was heated to a prescribed temperature while the pin was kept out of contact at room temperature. After stabilisation of the disc temperature, the pin was put in contact with the hot disc and the friction test started immediately. The initial contact between the pin and the disc was thus a contact between metal (pin) and iron oxide (disc). The pin temperature increased in several heat exchanges: thermal conduction, radiation, convection, and also generated friction heat (a weak influence). Tribological tests were performed under a normal load of 20 N with a disc rotation speed of 100 rpm (0.13 m/s). The effect of temperature from RT to 950 °C on the friction coefficient evolution and pin wear has been reported elsewhere [24,25]. The attention of this paper is focused on the results of the experiments performed at 700 °C with different test durations (120, 300, 600, 900 and 3600 s of friction) to measure the wear-loss of the pin. It is interesting to note, however, that the surface temperature of the pin increased from RT to 700 °C after about 5 min. Each test was carried out at least twice to assess the reproducibility of the experiments.

Pin surface and cross-section examinations (parallel to the friction direction) were performed with SEM and ESEM to get a better insight into the micro-structural changes in the sub-surface.

2.2. Materials

The pins are machined in 5% chromium double-tempered martensitic steel grade bars (X38CrMoV5, AISI H11) with an initial hardness of 47 HRC, delivered free of charge by Aubert&Duval. Discs are ferrito-pearlitic mild steels (XC18, AISI 1018). The X38CrMoV5 steel is widely used for forging dies, whereas AISI 1018 mild steel is used in forged condition in the automotive industry. The initial hardness of AISI 1018 is about 168HV. The chemical compositions of the two steels are reported in Table 1.

The X38CrMoV5 (AISI H11) steel micro-structure is constituted by randomly oriented lathes. The lath dimensions are about 2 μm in thickness and 15 μm in length (Fig. 2). This micro-structure has a very high density of tangled dislocations and also a large amount of small carbides, which provide a good strength to the steel at room and high temperatures [26].

2.2.1. Mechanical cyclic behaviour of X38CrMoV5 (AISI H11)

X38CrMoV5 (AISI H11) is prone to thermal [29] and mechanical softening [27,28]. Jean et al. [29] have reported the softening of this steel under several isothermal [27,28] and thermal fatigue conditions. The thermo-mechanical fatigue softening is reported in [30]. Detailed Low Cycle Fatigue (LCF) investigations under isothermal and non-isothermal conditions have revealed that X38CrMoV5 tool steel invariably presents a high degree of continuous softening from the early cycles, even at room temperature. The softening is due to the carbides coarsening and dislocation annihilations