Wear 330-331 (2015) 103–111

Contents lists available at ScienceDirect

Wear

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

The role of frictional power dissipation (as a function of frequency) and test temperature on contact temperature and the subsequent wear behaviour in a stainless steel contact in fretting

X. Jin*, P.H. Shipway, W. Sun

Division of Materials, Mechanics and Structures, Faculty of Engineering, University of Nottingham, Nottingham, UK

ARTICLE INFO

Article history:
Received 3 September 2014
Received in revised form
21 January 2015
Accepted 6 February 2015

Keywords:
Fretting wear
Contact temperature
Stainless steel
Frequency
Debris

ABSTRACT

Temperature is known to affect the fretting wear behaviour of metals; generally, a critical temperature is observed, above which there are substantial reductions in wear rate, with these being associated with the development of protective oxide beds in the fretting contact. This work has examined the gross-sliding fretting behaviour of a stainless steel as a function of bulk temperature and fretting frequency (with changes in the fretting frequency altering the frictional power dissipated in the contact amongst other things). An analytical model has been developed which has suggested that at 200 Hz, an increase in the contact temperature of more than 70 °C can be expected, associated with the high frictional power dissipation at this frequency (compared to that dissipated at a fretting frequency of 20 Hz). With the bulk temperature at either room temperature or 275 °C, the increase in contact temperature does not result in a transition across the critical temperature (and thus fretting behaviour at these temperatures is relatively insensitive to fretting frequency). However, with a bulk temperature of 150 °C, the increase in temperature associated with the increased frictional power dissipation at the higher frequency results in the critical temperature being exceeded, and in significant differences in fretting behaviour.

1. Introduction

Fretting is the small amplitude oscillation between two bodies in contact which occurs in a wide variety of mechanical systems. Although the amplitude of fretting is small ($<300\ \mu m$), fretting can cause serious damage including wear and fatigue. It has been stated that over 50 parameters can influence behaviour in fretting [1]; amongst them, the temperature of the contact has been identified as having a significant influence on both the rate and mechanism of damage in fretting. The role of temperature in fretting has generally been attributed to changes in the rate of formation of oxide in the fretting contact, and to changes in the way that the oxide debris is either expelled from the contact or retained within the contact.

Previous studies have suggested that the fretting wear rate of both carbon and stainless steel tends to fall rapidly once a certain critical ambient test temperature has been exceeded [2–5]. However, the fretting process itself also influences the contact temperature due to the dissipation of frictional power through the contact. This is dependent on the applied load, the coefficient of friction, the slip amplitude and the frequency of oscillation (with this paper focussing on the role of fretting frequency in this regard). As the fretting frequency increases, the temperature within the contact will also increase, and it is argued that this will affect the debris formation and debris retention within the contact by mechanisms similar to those proposed when the role of ambient temperature has been considered. Indeed, a general reduction of wear rate has been found with increasing fretting frequency in previous studies [6–8]. Frequency was chosen as the main controlling parameter as (all other things being equal) the frictional power dissipation is simply proportional to fretting frequency; this is in contrast to changes in load (which will affect the tractional force required for sliding of the contact, and will thus change the slip amplitude as well as the frictional force) and changes in displacement amplitude (which will affect the frictional power dissipation but will also affect the area over which that frictional power is dissipated); accordingly, variations in the frequency provide the simplest route to understanding the role of dissipated frictional power density on the temperature and subsequent fretting behaviour of such a contact.

As already identified, wear behaviour in fretting depends critically on the creation of oxide debris and the retention/ejection of that debris from the contact. It has been demonstrated by a number of workers (e.g. Colombie et al. [9], Iwabuchi et al. [5]) that the rate and mechanism of wear is very sensitive to the formation of a stable oxide debris layer. It was argued that a stable

---

* Corresponding author.
E-mail address: eaxxj@exmail.nottingham.ac.uk (X. Jin).

http://dx.doi.org/10.1016/j.wear.2015.02.022

debris bed acts as a third body between the two contacting parts in that it separates the wear surfaces and functions as a solid bearing to protect the primary surfaces [10]. However, if a stable debris layer cannot be formed, the existence of the oxide particles may increase the wear rate as they act in an abrasive manner. It has been proposed by Jiang et al. [11] that it is the inter-particle adhesion force that affects the formation of a stable layer. With a stronger inter-particle adhesion force, the oxide particles are more readily formed into a stable debris layer rather than being expelled from the contact. It is suggested that with increasing temperature, the surface free energy of the oxide particles increases, and that this will increase the adhesive force between the particles and encourage the formation of a stable debris layer [11].

Whilst sintering of particulate materials is generally only significant at temperatures above approximately a half of the melting point of the material [12], it has been demonstrated that sintering can occur at much lower temperatures, either with very fine particles [13,14] or under tribologically-active conditions [13–15]. By supplying fine iron oxide particles into a sliding interface, sintering has been demonstrated at room temperature by Kato [14] and Kato and Komai [13]. In addition, the study of Pearson et al. [16] on a high strength steel argued that debris sintering occurred at temperatures as low as 85 °C in fretting.

The effect of frequency on fretting behaviour has often been attributed to its effect on the kinetics of formation of oxide debris. Uhlig and co-workers [6,7] observed that the wear rate in a steel contact fell by about 58% with increasing fretting frequency from around 1 Hz to 50 Hz; moreover, the effects of the frequency were greater with larger displacement amplitudes (and thus larger frictional power dissipation in the contact). In addition, Feng and Uhlig [7] also demonstrated that the effect of frequency disappeared when the tests were conducted in an inert (nitrogen) atmosphere, clearly indicating that the frequency effects were intrinsically linked to oxide formation. In fretting, asperities in the contact interact, resulting in the exposure of clean metallic surfaces; the oxidation of that nascent metal is both a temperature-dependent and time-dependent process. High fretting frequencies can encourage the formation of oxides by raising the contact temperature; however, at the same time, an increase in fretting frequency reduces the time for oxidation between interactions of the asperities in the contact. The amplification of any effects of fretting frequency with displacement amplitude [17–19] is associated with the increase in frictional power dissipation (recognising that there are also changes in the area over which the power is dissipated associated with changes in displacement amplitude, but typically only for one of the bodies in the contact in a non-conforming contact).

It can be seen that both environmental bulk temperature and the fretting frequency have a critical influence on behaviour in fretting, and it is argued that these two influences are not entirely independent. The study of contact temperature associated with dissipation of frictional power in a contact has a long history, with its significance in wear being well-recognised. Blok identified the role of what was termed the “flash temperature” [20], and since that time, many mathematical models have been created to calculate the temperature rise associated with frictional power dissipation in both sliding and fretting contacts [21–25]. In the current work, both fretting frequency and environmental temperature were varied in order to explore the various influences on the contact temperature and the subsequent wear within a stainless steel contact. The effects of these two influences upon the magnitude and mechanisms of damage were explored, facilitating an understanding of the dominant influences.

Table 1
Chemical composition of 304 stainless steel (wt%).

C	Si	Mn	P	S	Cr	Mo	Ni
0.027	0.816	1.79	0.013	0.025	17.2	0.303	10.3
Al	Co	Cu	Nb	Ti	V	W	Fe
0.003	0.083	0.347	0.012	0.008	0.044	0.035	Remainder

2. Experimental procedure

2.1. Specimen, test procedures and conditions

Fretting experiments were conducted on 304 stainless steel specimens; the chemical composition of this steel is detailed in Table 1. Specimens were assembled in a cylinder-on-flat arrangement (Fig. 1) which generated a line contact with a length of 10 mm. The flat specimen was mounted on the lower specimen mounting block (LSMB) which is stationary and the cylindrical specimen was mounted on the upper specimen mounting block (USMB). A normal load, P, was applied to the USMB through a dead-weight. The fretting motion was applied perpendicular to the axis of the cylindrical specimen through control of an electro-magnetic vibrator (EMV). The far-field displacement of the USMB was measured through a capacitance displacement sensor which facilitated control of the relative displacement between the specimens. The EMV was guided axially by leaf springs to apply a displacement to the USMB as shown in Fig. 2. A piezoelectric load cell was used to measure the tangential force in the contact. The displacement and the tangential force were recorded continuously (200 samples per fretting cycle) and were plotted against each other as fretting loops. The maximum reaction force (Q^*) in each cycle was recorded. A schematic fretting loop (representative of those observed during the tests conducted) is presented in Fig. 3, along with an example of a measured fretting loop. The slip amplitude (δ) represents the actual slip that occurs in the contact; it is measured from the fretting loops and is usually smaller than the applied displacement amplitude (Δ) due to compliances in the contact and in the system more generally. The energy coefficient of friction (ECoF), calculated from the dissipated energy per cycle (E_d), was employed in this study as follows:

$$\mathrm{ECoF} = \frac{E_d}{4\,P\,\delta}$$

The stiffness of the system, S, is defined as the gradient of the steep side of the fretting loop (see Fig. 3a), which corresponds to measured displacements under conditions when the contact is not sliding [26,27]. Fig. 3b shows an example of an experimentally-measured fretting loop; from loops such as this, the system stiffness, S, can be estimated to lie in the range of 30–37 MN m^{-1}.

Cartridge heaters were integrated into the LSMB and a plate heater was assembled above the cylindrical specimen on the USMB to allow control of the temperature of each specimen. Open wire thermocouples were welded onto the top surface of each of

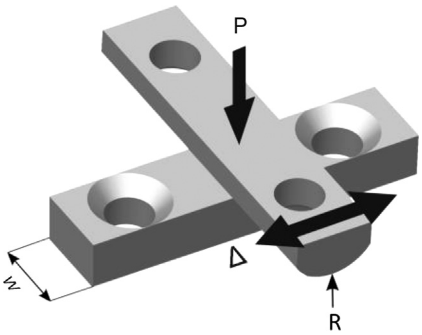

Fig. 1. Cylinder-on-flat specimen arrangement in fretting test: $W = 10$ mm, $R = 6$ mm, $P = 450$ N, and $\Delta = 50$ μm [8].