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Effect of test conditions on the temperature at which a protective debris bed is formed in fretting of a high strength steel

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ABSTRACT

It is well known that mechanisms and rates of fretting wear of many metals are dependent upon the temperature of the environment; specifically, it is known that a transition temperature exists, above which the debris forms a protective bed in the contact which results in very low rates of wear being observed. This paper seeks to investigate the influence of contact geometry and slip amplitude on the transition temperature of a high strength alloy steel, and to understand these effects in terms of debris retention in (or expulsion from) the contact. Cylinder-on-flat fretting tests were performed at temperatures between 25 °C and 250 °C with two displacement amplitudes (25 µm and 100 µm) and two cylinder radii (6 mm and 160 mm). It was found that for the smaller cylinder radius, the transition temperature increased as the fretting displacement amplitude was increased. However, it was found that whilst the contacts with 6 mm radius cylinders and 160 mm radius cylinders exhibited very different mechanisms of wear at low temperature, the temperature at which the transition to forming of the protective debris bed was not strongly influenced by the contact geometry; moreover, at the higher temperatures, the protective bed is formed irrespective of contact geometry. It is proposed that the reduction in wear rate at higher temperatures is associated with the retention of oxide debris within in the contact area for long enough that it sinters to form a protective 'glaze' layer. By increasing the displacement amplitude, the rate at which the oxide is ejected from the fretting contact increases and this reduces the ability to form a protective layer; as such, a higher temperature is required to form the protective glaze as the displacement amplitude is increased.

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1. Introduction

It has long been known that sliding wear behaviour of metals is strongly influenced by the formation of oxide-based debris, and the way that the debris either flows out of the contact -[1] or forms compacted debris beds (sometimes known as glaze layers) within the contact [2,3]; the formation of compact oxide debris beds on a wearing surface is promoted by elevated temperatures and generally results in a significant reduction in the rates of wear. Fretting differs from sliding in that fretting is defined by small amplitude (often defined as less than 300 µm [4]) oscillatory motion between the bodies in contact whereas in sliding the motion is of a much larger scale (and may even be unidirectional). Consequently, wear debris is more readily retained in the contact in fretting than it is in sliding, and thus its transformation to a protective glaze occurs more readily. Indeed, in recent work, Pearson et al. [5] reported that there was an 87% reduction in the rate of fretting wear of a high strength steel on increasing the temperature from 24 °C to just 85 °C (with very little further reduction as the temperature was raised further); they suggested that high temperatures resulted in an adhesive force between the oxide debris particles which inhibited their removal from the contact zone, and allowed them to be retained in the contact long enough for a stable load-bearing tribofilm to be created by particle sintering. This is in accord with other work [6–8] which suggests that the sintering to form a tribofilm occurs above a specific transition temperature. Whilst the transition temperatures appear to be low compared to those normally associated with particle sintering, the work of Zhou et al. [9] on the sintering behaviour of ultra-fine iron powders (not in the context of fretting) demonstrated that sintering of very fine (40 nm) iron particles can take place even at room temperature.

In addition to temperature, the macroscopic geometry of a fretting contact has been shown to influence the way in which the debris is formed and escapes from the contact. Fouvry et al. [10,11] carried out tests with Ti–6Al–4V using a ball-on-flat configuration with varying ball diameters to cover a range of contact sizes and

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demonstrated that as the contact size increased, the coefficient of friction and the wear rate both decreased. In a similar vein, Warmuth et al. [12] carried out fretting wear experiments of high strength steel, which involved cylinder-on-flat specimens in which the cylinder radius was varied between 6 mm and 160 mm and the displacement amplitude was varied between 25 μm and 100 μm. They observed that more conforming contact geometries (larger cylinder radii) were associated with lower rates of wear which led to subsurface deformation and adhesive transfer in the form of pitting and peaks rather than bulk material removal associated with fretting of less conforming contacts. They argued that the effects observed were not influenced by the changes in contact pressure associated with the different cylinder radii, but instead rationalised their observations both in terms of oxygen ingress into the contact during fretting and in terms of debris egress from the contact, with both of these being less favourable as the size of the contact increased (associated with increasing cylinder radius). However, they also suggested that the fretting displacement amplitude did not change the mechanisms of fretting wear.

It is evident that the retention of oxide-based debris within the contact is a key issue when considering the way in which temperature affects fretting behaviour. Whilst Pearson et al. [5] observed a particular transition temperature above which a protective glaze formed, it should be noted that they conducted experiments with only one contact geometry and at only one fretting amplitude. Given that the formation of the glaze-like debris bed is associated with the way that the debris is retained in the contact (and whether it is retained for long enough for sintering to take place), it is hypothesised that the transition to forming a stable debris bed will depend not only upon temperature, but also upon both the fretting amplitude and the contact geometry (as these will both also affect the debris egress); the validity of this hypothesis will be examined in this paper.

2. Experimental method

2.1. Materials and specimens

To allow direct comparison with previous work [5,12,13], all the specimens were manufactured from a high strength steel (S132) which is commonly employed in aerospace applications where fretting of highly-loaded contacts may occur; the composition of this steel is given in Table 1. Initially, the material was cut into blanks and heat treated. The heat treatment consisted of a pre-heat to 940 °C, at which the samples were held for 45 min and then quenched in oil. They were then tempered for 120 min at 570 °C and then cooled in air; the Vickers hardness (20 kgf applied load) of the samples following heat treatment were 465–477 kgf mm^{-2}. Fig. 1 shows the final dimensions of the samples after grinding where R may have the value of 6 mm or 160 mm (these values being selected as the largest and smallest employed in the work of Warmuth et al. [12]).

Table 1
Composition of high strength S132 steel (wt%).

C	Si	Mn	P	S
0.35–0.43	0.1–0.35	0.4–0.7	< 0.007	< 0.002
Cr	Mo	Ni	V	Fe
3.0–3.5	0.8–1.1	< 0.3	0.15–0.25	Remainder

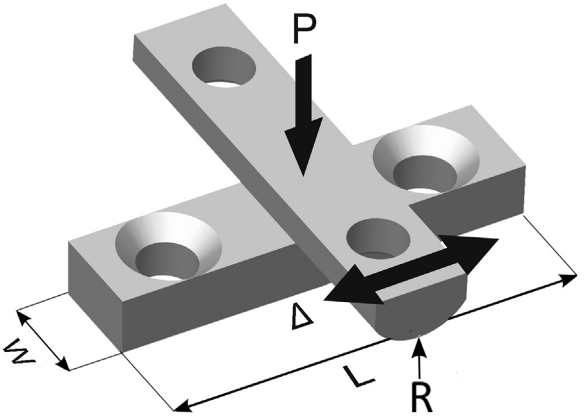

Fig. 1. Diagram of the specimens and their positions in the fretting test. W = 10 mm, R = 6 mm/160 mm, P = normal load, Δ = applied displacement.

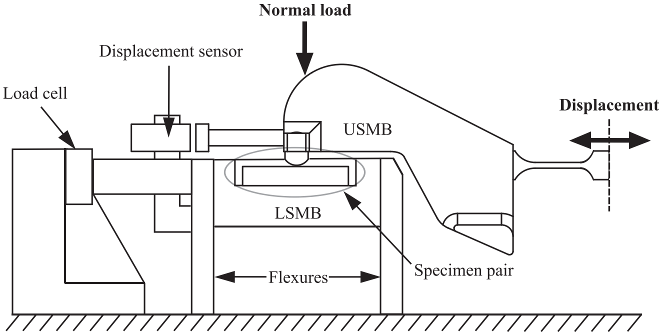

Fig. 2. Schematic diagram of the fretting rig.

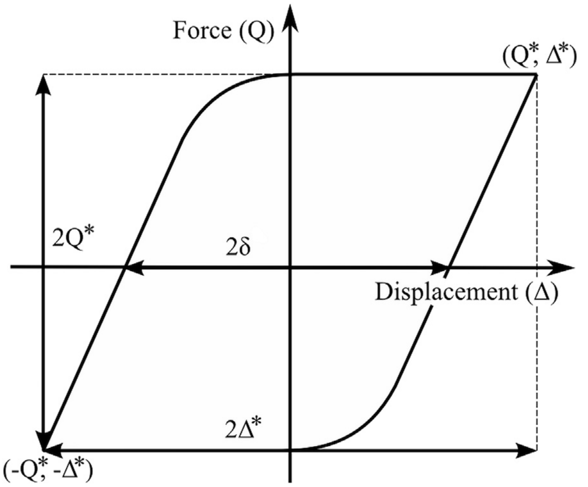

Fig. 3. Gross sliding fretting loop.

2.2. Fretting tests

All tests were carried out using a cylinder on flat arrangement (as shown in Fig. 1), with the general experimental setup for the fretting tests being shown in Fig. 2. Before testing, all specimens were degreased with detergent and methylated spirit. The flat specimen was attached to the lower specimen mounting block (LSMB) and the cylindrical specimen was attached to the upper specimen mounting block (USMB) which is moved relative to the LSMB using an electromagnetic vibrator (EMV) which maintained a constant applied displacement amplitude (Δ^*) (see the idealised fretting loop in Fig. 3 for definition of the displacement amplitude) with the displacements being measured with a capacitance

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