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The influence of surface hardness on the fretting wear of steel pairs—Its role in debris retention in the contact

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ABSTRACT

The influence of specimen hardness (between 275 kgf mm^{-2} and 835 kgf mm^{-2}) in an AISI Type O1 steel-on-steel fretting contact was examined. In equal-hardness pairs, a variation in the wear volume of around 20% across the range of hardnesses examined was observed. However, in pairs where the two specimens in the couple had different hardnesses, a critical hardness differential threshold existed, above which the wear was predominantly associated with the harder specimen (with debris embedment on the softer specimen surface). This retention of debris provides protection of that surface from further wear and also results in accelerated wear of the harder counterface due to abrasion by the oxide debris bed which has built up on the opposing specimen.

1. Introduction

Fretting wear is a unique form of material degradation caused by small amplitude oscillatory relative motion of two surfaces in contact. Fretting wear is typically encountered at relative displacements of less than 300 μm [1] and occurs in either a gross slip regime (where there is slip displacement across the whole contact), or a partial slip regime (where there are parts of the contact where no slip displacement occurs). Fretting wear is experienced within a wide range of industrial sectors, including aeroengine couplings [2], locomotive axles [3] and nuclear fuel casings [4]. Under higher loads and smaller displacement amplitudes, the contact will be within the partial slip regime, often resulting in fretting fatigue where the dominant damage mode is a reduction in fatigue life [5]. Fretting in the gross slip regime generally results in larger amounts of material removal (wear) and debris formation; this will be the focus of this investigation.

When analysing fretting wear, the two contacting surfaces are termed *the first-bodies*, and when debris is generated within the contact, it is described as an additional *third body*. Debris can be formed from either one or both of the two first-bodies and is either entrapped within or ejected from the contact area. It is well documented that debris plays a key role in the fretting wear behaviour of a fretting couple [6–8]. The presence of debris may promote wear if it is hard and acts as an abrasive or, in contrast, it may effectively separate the two first-bodies and prevent or reduce wear.

Previous research by Dobromirski has suggested that there are upwards of 50 variables that affect the fretting wear process [9], including contact pressure, temperature and surface hardness. Whilst Archard's wear equation (developed for sliding wear) has been successfully used to predict material loss in fretting [10], there are findings to suggest that the relationship between the resistance to fretting wear and material hardness is complex. Studies by Kayaba and Iwabuchi have shown that when two steels of different hardnesses were fretted against each other, the harder steel wore more than the softer contact [11]; they attributed this effect to protection of the surface by a black oxide debris layer. In their experimental programme, they used different types of steel for each of the specimens in their couple and both steels were heat treated to produce a range of hardnesses between around 200 and 800 kgf mm^{-2}; one steel had a high chromium content of around 0.9 wt% whereas the other had a chromium content <0.05 wt%. As such, it was not clear whether differences in behaviour were associated with material hardness or other changes (such as oxidation kinetics) associated with the differences in steel composition. In similar work, Ramesh and Gnanamoorthy described the fretting behaviour of two different steels; specifically, a structural steel with differing hardness produced via heat treatment was fretted against a bearing steel of a fixed hardness (the hardness of the bearing steel was always higher than that of the structural steel) [12]. Whilst they did not compare the wear rate of

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the structural steel and bearing steel, they saw no evidence of appreciable variation in wear rate with hardness of the structural steel (with Vickers hardness ranging from 207 to 640 kgf mm^{-2}), and concluded that the wear rate is dependent primarily on the properties of the hard oxide debris. In more recent work, Budinski [13] conducted steel-on-steel fretting tests with a hard steel against a different counterface steel; the hardness of the counterface was varied, with its highest hardness being equal to that of the other body. A decrease in overall wear rate was observed as the hardness of the steel was decreased from its highest value until a critical value of hardness was reached, whereupon the overall wear volume significantly increased. However, the wear volumes of the two individual members of the couple were not reported.

In a similar fashion, both Varenberg et al. [6] and Elleuch and Fouvry [14,15] fretted a hard steel against a softer non-ferrous-metal; Varenberg et al. [6] fretted steel against bronze (having Vickers hardnesses of 529 and 135 kgf mm^{-2} respectively) whilst Elleuch and Fouvry [14] fretted steel against an aluminium alloy (with Vickers hardnesses of 856 and 115 kgf mm^{-2} respectively). Both research teams found that under certain fretting conditions, the hard steel wore substantially more than the softer counterbody, concluding that this effect is due to the formation of oxide debris which then became trapped in the contact area and embedded in the softer surface; the hard, embedded particles then abraded the harder mating steel surface, resulting in high rates of wear on the hard steel and much lower rates of wear on the softer non-ferrous counterbody.

In contrast to the research findings for metal–metal contacts, Endo and Marui showed that in fretting of steel against much harder ceramics, the softer steel specimen wore substantially more than the harder ceramic [16]. However, no evidence was found of hard, ceramic debris becoming embedded in the softer steel; instead, transfer of the softer steel onto the surface of the hard ceramic was observed. These results indicate that although hardness is a factor in fretting wear, the hardness acts primarily to influence the role of the debris which then governs the fretting wear damage.

The focus of the current work is an investigation of the role of the hardness of steel on its fretting wear behaviour. Unlike previous work on steel-steel contacts in this area [11–13], the same steel employed for both parts of the fretting couple (thus avoiding any concerns about the chemistry of the steel affecting debris formation and retention), with hardnesses of both specimens in the fretting couple being varied through heat treatment. Fixed fretting wear parameters (load, displacement amplitude and frequency) were employed for the majority of the tests conducted, with the only variable being hardness of the two contacting bodies; however, a small number of tests were performed with a different fretting frequency in an attempt to provide evidence to support hypotheses being developed.

2. Experimental procedure

The steel studied in this investigation was AISI O1 steel; the composition of the steel was measured through spark emission using a WAS Foundry-Master with the results being presented in Table 1. Quenching and tempering of the steel was used to vary its

Table 1
Measured chemical composition of AISI Type O1 Steel (wt%)

Cr	C	W	Mn	Cu	V	Fe
0.5	0.9	0.6	1.1	0.2	0.1	Balance

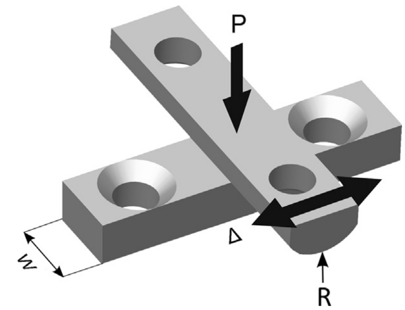

Fig. 1. Crossed cylinder-on-flat specimen configuration utilised in the fretting experiments.

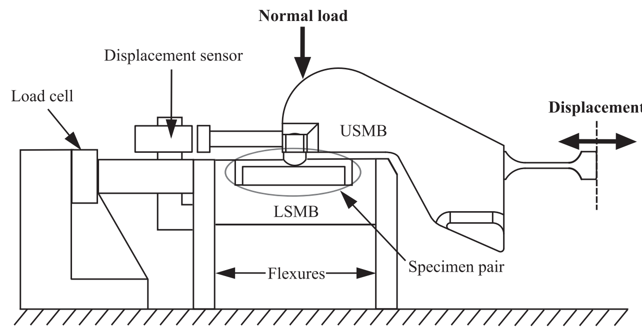

Fig. 2. Illustration of the main components of the fretting apparatus used in this study.

hardness. The specimens were preheated to 500 °C for 30 min, austenitized at 790 °C for 30 min, quenched and tempered at a selection of temperatures for 1 h. The temperatures chosen were 240 °C, 400 °C, 540 °C and 680 °C which resulted in Vickers hardnesses of the steel (measured under a 20 kgf load) of 695 kgf mm^{-2}, 555 kgf mm^{-2}, 415 kgf mm^{-2} and 275 kgf mm^{-2} respectively. The hardest specimens (835 kgf mm^{-2}) were created by austenitizing and quenching only.

Following heat treatment of steel blanks, test specimens were machined into flat and cylindrical specimens by linear and cylindrical grinding respectively. The specimen pair was assembled in a cylinder-on-flat configuration, as shown in Fig. 1. Cylindrical specimens were manufactured with a radius, *R*, of 6 mm and the flat specimens had a width, *w*, of 10 mm (this controlled the length of the line contact). The flat specimen is mounted on the lower specimen mounting block (LSMB) which is stationary and the cylindrical specimen is mounted on the upper specimen mounting block (USMB). The USMB was loaded through a dead weight configuration and the normal load that resulted is termed *P*, which was 450 N in the experiments reported in this paper. It is recognised that there will be very large stresses associated with the edges of the flat specimen. However, the profile in this area is expected to wear rapidly to eliminate the sharp edge; no evidence of preferential wear in this area has been observed in any of the work reported that has used this geometry or in the work that is presented in this current paper.

The main components in the rig used for the fretting experiments are illustrated in Fig. 2. The motion of the USMB (and hence the cylindrical specimen) is created by a force generated by an electromagnetic vibrator (EMV). The displacement of the USMB is monitored by a capacitance displacement sensor which is mounted to the LSMB and is recorded throughout the duration of the test. The amplitude of the force input was controlled to achieve a set displacement amplitude of 50 μm to ensure that all tests were in the gross slip regime.

The lateral force, *Q*, is measured and recorded throughout the entire test by a piezoelectric load cell which is connected to the