EXPERIMENTAL INVESTIGATION OF SOME PROCESSES INVOLVED IN THE STEADY STAGE OF STEEL FRETTING

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I. Introduction

Oscillations of small amplitude, and usually of high frequency, cause a special type of wear of machine parts known as fretting wear. Fretting is different from any other form of wear; it is accompanied by a strong oxidation (i.e. chemical reaction) and it retains a majority of the debris brought about by the wear action: on steel surfaces black or reddish-brown deposits may be observed. The fretted metal surface exhibits characteristics very similar to wear, including metal transfer, abrasion, increased roughness and pitting. Fretting causes seizure and failure and results in a drastically reduced fatigue strength of machine parts.

The fretting process has an initial and a steady stage. The initial stage is characterized by adhesion and metal transfer processes between the fretted surfaces, which is of importance for subsequent wear damage. In the steady stage there is a stabilized wear action; oxidized and partly oxidized wear products or debris are formed between the fretted surfaces at a constant rate. Both stages of fretting are influenced by a large number of variables. The method of examination and testing, and the design of laboratory fretting apparatus may influence stages in the sequence of processes occurring in fretting and the degree of retention of the debris formed. Thus, quantitative assessment may differ for different types of apparatus. The data of different investigations and comprehensive reviews published in the literature vary and are often contradictory.

It is reported [1, 2, 3] that increased load increases the fretting wear damage, but also that load has no influence on damage [4, 5]. When slipping motion is eliminated by load, fretting damage is reduced. Generally, it has been established that increase of amplitude increases the wear [2, 4, 6]. But it has also been found that the greatest wear occurs at medium amplitude [7]. It has usually been observed that frequency has no influence on the fretting wear [8, 9]. However, it has been reported that damage decreases with increasing frequency [2, 6] and also that damage increases with increasing frequency [1, 2].

Many factors such as the shape or the geometry of the mating surface, surface treatment, material heat treatment, etc., have been investigated for their influence on the wear rate of actual mechanisms and laboratory specimens. However, little information is available, likely helping to predict the rate of fretting of steel.

In this study the effect of the characteristics of the oscillating motion, the surface pressure and the surface hardness has been investigated in the steady stage of dry fretting (without lubrication) of steel in a laboratory rig. The purpose was quantitative assessment of the fretting characteristics and qualitative assessment of the fretting mechanism.

II. Experimental apparatus and procedures

Fretting tests were conducted on an MTS closed-loop axial hydraulic material testing system Model 483.01 made by MTS, Minneapolis, USA, which provided the longitudinal oscillating motion. For producing the desired surface pressure between the fretting specimens a specially designed apparatus was used (Fig. 1). The apparatus allows two simultaneous, parallel experiments on the specimens 1—1′ and 2—2′. The spring arms a—a′ of the apparatus provide the desired load or surface pressure, the arms b—b′ keep the immovable spec-

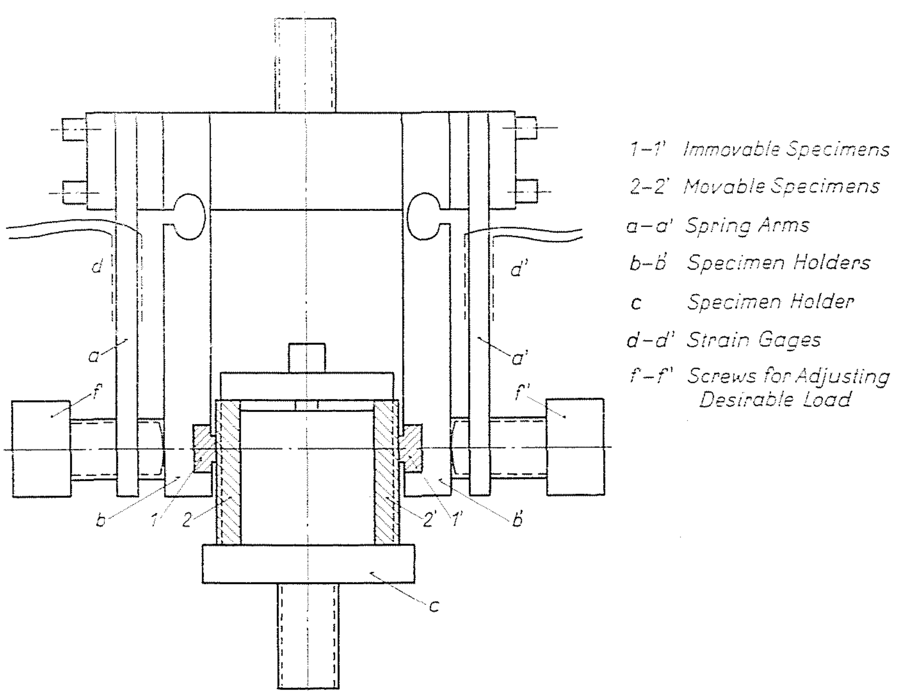

Fig. 1. Schematic diagram of the experimental set-up

imens 1—1′ in the correct vertical position. The counter-partners, movable specimens 2—2′ are mounted on the ram of the MTS apparatus by device *C*.

The load, i.e. the specific surface pressure, was measured with strain gauges d—d′ mounted on the springs a—a′. The friction forces of the two fretting processes were measured by a universal load cell mounted in the MTS apparatus.

After calibration the strain gauges d—d′ measured the distance changes between the arms, i.e. the wear rate of the specimens due to the fretting: the decrease of distance between the arms a—a′ assuming that the wear rate of both surfaces was the same.

Variation of the friction forces and wear rate were recorded for the duration of all tests by a Bursh high-speed recorder (Mark 280). Variation of the friction forces against slip were recorded by a *F. L. Moseley* Autograf X—Y recorder Model 2D—2 at low cycling speed. The fretting debris was examined visualy and microscopically.

The following materials were tested:

1. Mild steel SAE 1080, cold finished

$C = 0.15\%$; $Mn = 0.75\%$; $P = 0.008\%$; $S = 0.027\%$

Hardness: 115 HB.

2. Alloy steel SAE 4340, annealed, quenched and tempered

$C = 0.38-0.43\%$; $Mn = 0.60-0.80\%$; $P = 0.035\%$; $S = 0.040\%$′ $Si = 0.2-0.35\%$; $Ni = 1.65-2.00\%$; $Cr = 0.7-0.9\%$; $Mo = 0.2-0.3\%$.

Hardness:

annealed 230 HB.	21 HRC
quenched	55 HRC
tempered	35 HRC

The shape and dimensions of movable and immovable specimens are given in Fig. 2. The specimens have a 0.0156 sq. in. contact surface. The mating surfaces were finished by grinding. Results of preliminary experiments indicated that mechanical polishing does not affect the fretting process, especially in its steady stage. In all experiments, the mating surfaces were carefully cleaned with acetone prior to assembly. As the main purpose was the study of the steady stage of fretting, no special methods of surface preparation were necessary.

The experimental set-up had the following advantages for fretting research:

1. Accurate regulation of oscillating motion, i.e. stroke length, frequency and surface pressure.

2. The correct measurement of rate and amount of wear and of the friction force during the fretting process.

3. A means of studying the effect of different shapes of the oscillating motion.

— The equipment is readily adjustable permitting to carry out a large number of tests on the same specimens within a relatively short time, at a good reproducibility.

Some disadvantages, however, also exist.

As the movable specimens are oscillating and wearing only a definite length of the surfaces of the specimens 1—1′, the movable specimen at each end of the stroke contacts the unworn edge of the specimens 1—1′. This striking effect increases damages and results in increased friction forces at the end of each stroke. The greater the wear, the greater the difference between the friction forces at the middle and at the end of the stroke. This effect is shown in Fig. 3. Measuring friction forces and wear at the stroke mid-length, i.e. in the middle of the fretted surface, does not affect the results.

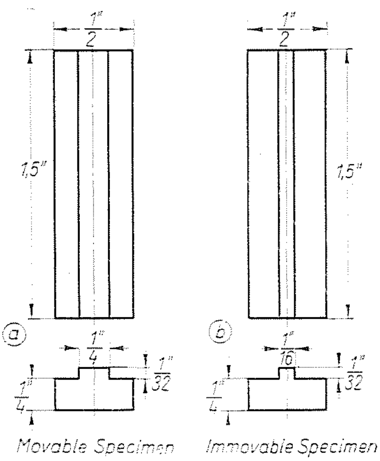

Fig. 2. Fretting specimens

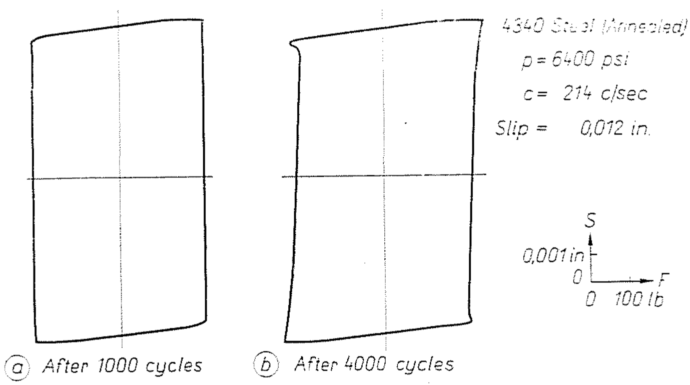

Fig. 3. Friction force (F) and stroke (S) diagram 4340 steel (annealed): p = 6400 psi; c = 214 cps; slip = 0.012 in

The high friction forces entrain elastic deformation of the arms b—b′ and elastic-plastic deformation of surface layers of the specimens. Wear could only be measured if the stroke length of the oscillatory motion was greater than 0.0005 to 0.0008 in.

The load is not constant during fretting; there is a slight decrease of the load, i.e. the surface pressure due to wear as the fretting proceeds. 1 mil wear on each surface was found to reduce the surface pressure by 1.15% (Fig. 4).

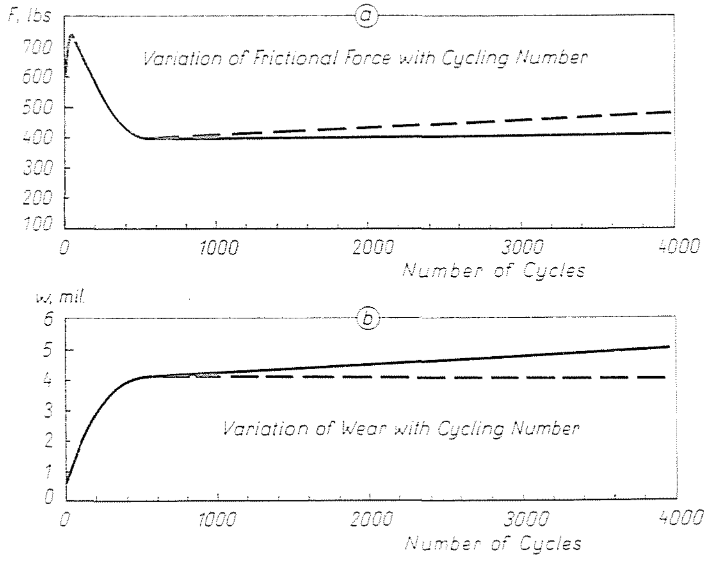

Fig. 4. Effect of duration of test on fretting 4340 steel; $p = 6400$ psi; $C = 20$ cps; slip = 0.012 in

This drop of surface pressure during the experiments does not affect the wear mechanism and rate. All experiments were made at room temperature in air at 50 to 60 per cent humidity.

Fretting was investigated under conditions of

— stroke length (slip) of 0.001 to 0.02, in,

— surface pressure of 640 to 8320 psi, and frequency 0.01 to 60 cps.

Most experiments were made using sinusoidal oscillatory motion, but some tests, using saw-toothlike oscillation at low frequencies, to study the effect of motion.

The duration of the tests varied from 100 to 5000 cycles depending on the frequency. At high frequencies of 10 cps or more the wear was measured during 3000 or 5000 cycles; at low frequencies, less than ten, usually several hundred cycles were enough to evaluate the wear.

III. Evaluation of test results

Effect of test duration

At the beginning of the fretting process there is a rapid increase of the frictional force reaching a maximum between 50 to 100 cycles depending on the material characteristics and frequency (Fig. 4). The frictional force becomes almost constant after 200 to 1000 cycles. At the end there is an "increase" of friction force due to the "knocking" effect of the unworn edge of the immovable specimens, indicated by dotted line in Fig. 4a. Variation of the wear amount follows the variation of the frictional force. During the first 200 to 1000 cycles there is a rapid wear attributed to the adjustment of the specimen to increased contact by smoothing of the surface and the build up of the oxidation process. This stage is followed by steady fretting, at a linear relationship between wear and cycle number. A dotted line represents the measured wear at the stroke ends. Possibly the initial increase of friction forces and the large wear rate is a characteristic of the test procedure and the fretting apparatus. This increase is 30 to 80% of the friction force measured during steady fretting, a value less than that found by HALLIDAY [10].

In general it was found that the softer the metal tested, the greater the surface pressure and the lower the cycling speed, the greater the initial increase of the frictional force and wear. The friction force and wear rate are rather scattered in this first stage of fretting. This scatter is probably due to the characteristics of the fretting apparatus, the adjustment of the four specimens, and the non-uniform contact surfaces between each two specimens.

Effect of amplitude of oscillation

The fretting wear in its steady stage was found to be related linearly with slip, i.e. with the amplitude of the vibratory motion. The greater the amplitude of oscillation, the greater the wear rate. Figs 5, 6 show wear at different frequencies and surface pressures. Fig. 7 shows the effect of the heat treatment of the material on wear at 20 cps and 5120 psi specific surface pressure.

At less than 0.002 in. slip, no exact measurement of the fretting wear under the experimental conditions was possible. Extrapolation indicates that fretting wear begins at around 0.001 in. slip under the conditions of surface pressure investigated.

Effect of frequency

Fretting wear is greater at low, and lower at high frequencies (Fig. 8); frequency is plotted in logarithmic scale. For hard metals there is an almost linear relationship between wear and frequency. Increase of frequency over 20

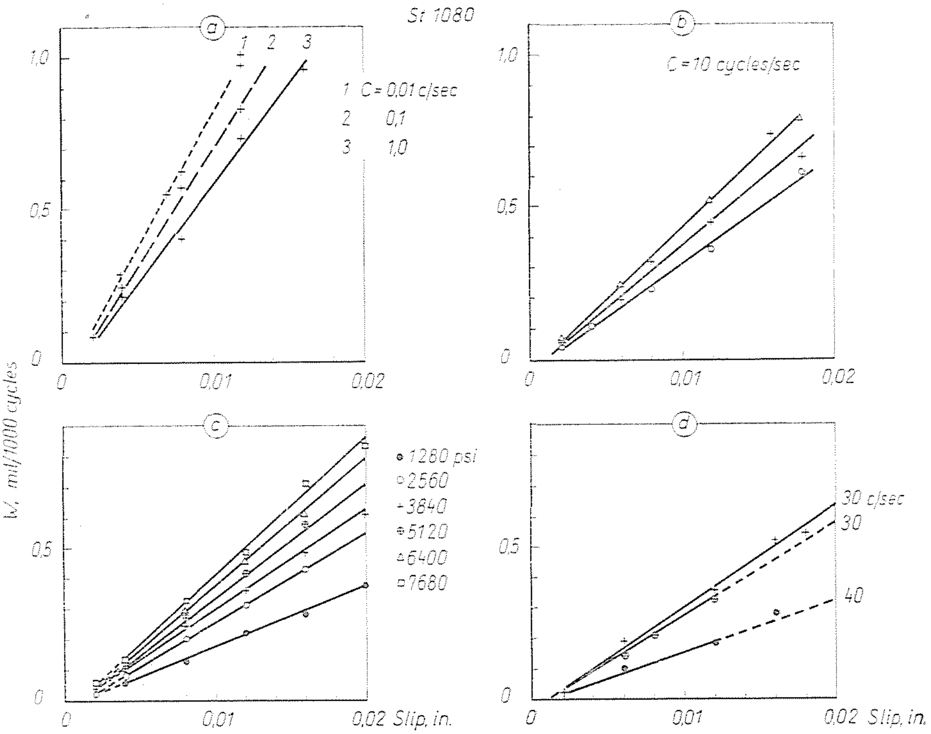

Fig. 5. Effect of amplitude (slip) on fretting wear

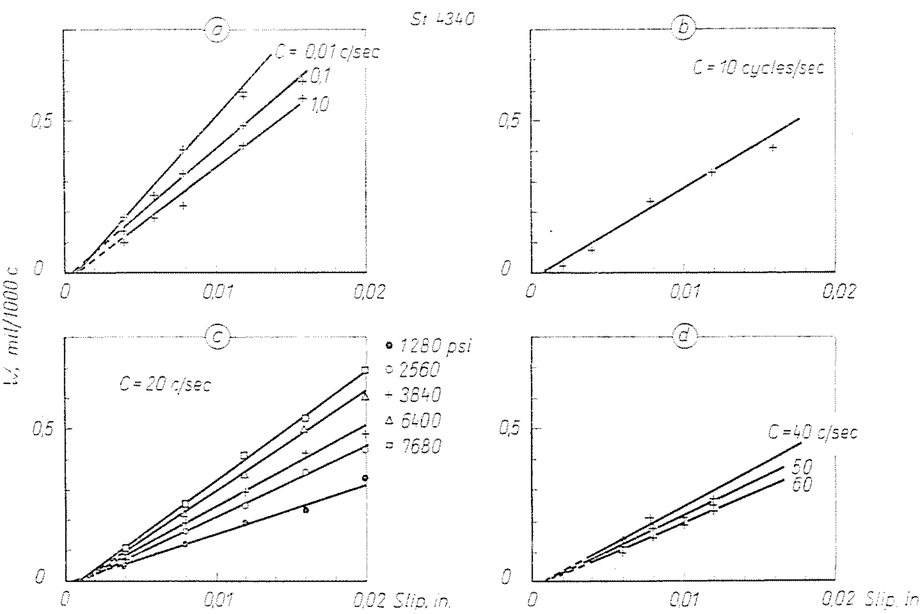

Fig. 6. Effect of amplitude (slip) on fretting wear

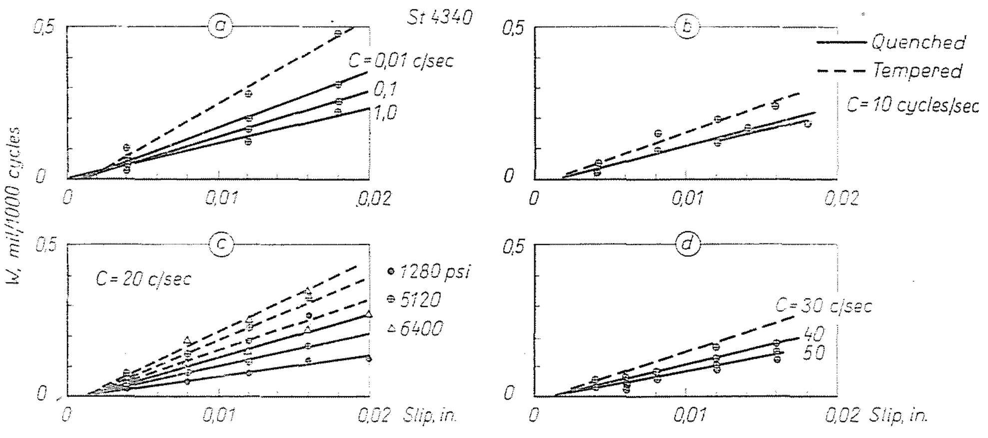

Fig. 7. Effect of amplitude (slip) on fretting wear

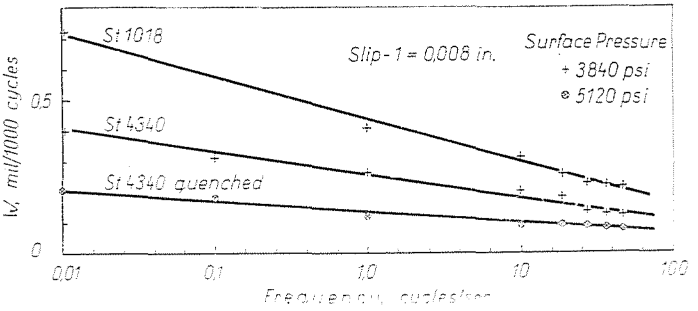

Fig. 8. The effect of frequency on fretting wear

to 30 cps does not significantly affect fretting even for soft steel. Several experiments were carried out at 70 and 80 cps at low amplitudes on quenched steel and the results showed good logarithmic correlation. As with pressure, the effect of frequency is greater for soft metals than for hard metals.

The effect of surface pressure

Fig. 9 shows fretting wear in terms of specific surface pressure. In the case of soft steel (1080) the form of the wear is parabolic according to the surface pressure graph. The relationship is almost linear for quenched steel under the pressures investigated.

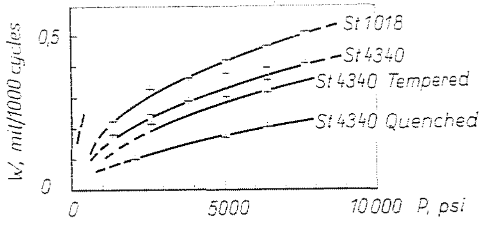

Fig. 9. Effect of specific pressure on the fretting wear. slip = 0.012 in. C = 20cps

Due to elastic losses, for amplitudes less than 0.002 in, the load effect on the fretting wear could not be determined. In the experiment, the effect of load on the wear differed from that expressed by UHLIG [2].

Effect of the shape of the oscillatory motion

To investigate the effect of oscillation, several experiments were conducted at low-frequency saw-tooth motion. The results are presented in Fig. 10. In experiments on 1080 steel, fretting wear was less for saw-tooth motion. Quenched 4340 steel exhibited more wear. Measurements began after 500 cycles to eliminate original surface roughness effects.

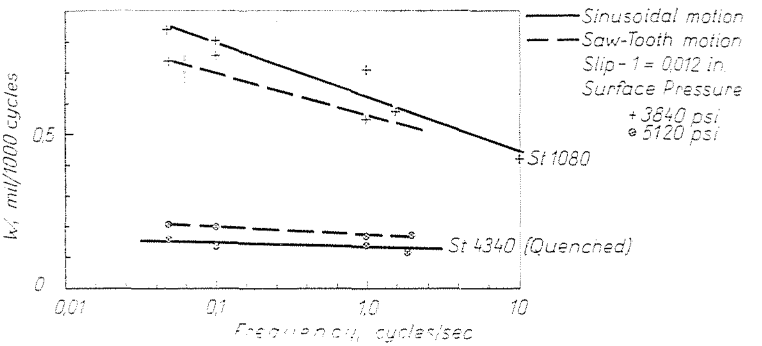

Fig. 10. Effect of the shape of the oscillating motion

Examination of debris and fretted surfaces

Examination of the debris formed and the fretted surfaces showed that of the characteristics of vibration, frequency had the greatest effect on the formation of debris in the steady stage of fretting. At low frequencies (0.01 to 1 cps) or at low speed, fretted surfaces are rough ($R_a = 0.5$ to 0.3 μm) with a metallic appearance or they are partly oxidized. The debris consist of unoxidized or partly oxidized metallic iron. At an increased frequency, 10 to 20 cps, more partly oxidized or fully oxidized debris was found. The wear products had a black colour and have been reported to be α-Fe_2O_3 [11]. At 20 cps and higher frequencies, as fretting proceeds, the debris become finer, have a reddish-brown colour and are α-Fe_2O_3 with a particle size as small as 0.01 in diameter.

Load and amplitude have an opposite effect. Increase of surface pressure and length of stroke changes the formation of oxidized debris in the range of higher frequencies. Fretting under 6400 psi surface pressure produces debris of more metallic content than that produced at 1280 psi. Thus, the debris is more metallic at great than at small amplitudes.

Increasing the hardness of the metal promotes the formation of oxidized debris. Fretting of hard, quenched steel at 20 cps frequency produces reddish-brown oxide; under the same conditions debris from the 1080 steel is black and contains more metallic material. Fretted surfaces differed significantly. Those of quenched 4340 steel were coated with reddish-brown oxide; those of 1080 steel with black oxide and metallic spots alone.

IV. Discussion of results

In the steady stage of fretting the debris formation is characterized by a complex and general disintegration and dispersal of surface zones. The oxide becomes embedded in the metal surface to such an extent that the rubbing surface cannot be considered as a sharp boundary between metal and oxide any more but rather as a zone in which metal and oxide, metal oxygen solid solution are intimately mixed. This indicates that in steady stage the mechanism of fretting wear is strongly dependent on the formation of metal oxygen solid solution, on the oxidation process, and on the mechanical wearing actions of the rubbing surfaces.

The mechanism of fretting in the steady stage can be described as follows [1, 12]:

(a) — Adhesion and metal transfer by cold or warm welding occurs by the formation and shearing of junction between contacting surfaces upon the rubbing action of oxide films and metallic asperities. A weak junction produces a loose wear particle, while a strong junction may lead only to metal transfer. Debris produced by this process will be largely unoxidized.

(b) — The oxide films which grow on the metal surfaces may be continually broken up and rubbed off by the ploughing action of surface asperities and thus, by exposing fresh metal surfaces, the oxidation process activated by the rubbing action is allowed to continue. The debris will consist of oxide.

(c) — During vibratory motion the alternating tensile and compressive stresses first induce fatigue cracks in the rigid oxide or oxygen-metal solid solution layers. These micro-cracks result in the separation of loose, fine oxide debris.

(d) — The oxidized debris and the work-hardened, unoxidized, or partly oxidized debris accelerate the wear process by acting as an abrasive material cutting and scratching the surfaces. The product will be fine metal chips or oxidized debris.

The mechanisms of fretting are probably more complex; and each of the above mechanisms has a definite role in the fretting process.

On the basis of the present results the following assumption can be made:

As the amplitude of the vibratory motion has the greatest effect on the wear rate, and frequency is the main determinant of the nature of the debris and the fretted surface, it may be concluded that the principal wear mechanisms of steady stage fretting are adhesion and metal transfer between the contacting surfaces and separation of the oxide layer by fatigue. At large amplitudes of vibration there is an increased probability of adhesion junctions as adhesion points may be created and destroyed several times within a single cycle. Thus, cracking, break up and disintegration of the oxide layer by fatigue action is accelerated. The probability of the build-up of adhesion-type welding between the mating surfaces and of the development of alternating tensile and compressive stresses will be greater with increased length of stroke.

Oscillatory characteristics which cause build-up of adhesion junctions give increased wear. At lower frequencies, low speed favours the formation of adhesion points which explains the lower data with saw-tooth motion. A higher surface pressure increases the probability of adhesive junction build-up.

Load also plays a part in the activation of oxidation reactions and the break-up of the oxide layer.

High initial surface hardness decreases the fretting rate. Hard surfaces of the same crystal structure give lower values of adhesion and coefficients of friction than soft surfaces. For the harder steels plastic deformation is restricted and the real area of contact remains small. Although individual metal junctions may be quite strong, adhesion and wear rates remain low.

Acknowledgment

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Summary

The present study was undertaken to investigate the effect of oscillatory motion, surface pressure and surface hardness on the steady stage of dry fretting of steel in a laboratory rig.

Increased slip, greater surface pressure and lower cycling frequency, all promote the adhesion mechanism of fretting. At higher frequencies, slip and low surface pressures decrease, the product of fretting wear is mainly oxides and oxidation is the leading wear mechanism.

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