FRETTING AND FRETTING FATIGUE OF TITANIUM ALLOYS UNDER CONDITIONS OF HIGH NORMAL LOAD

Suehiro Goto* and Robert Barry Waterhouse

Department of Metallurgy and Materials Science,
University of Nottingham, Nottingham NG7 2RD, U.K.

Abstract

There are many factors which can influence contact failures. They include the nature of the contracting materials, stress conditions in the contact zone and also whether or not the contact is lubricated. If a lubricant is present then its chemical composition is also relevant. Possibly the most important factor is the magnitude of the tangential force.

Fretting was produced by the tangential vibration of a hardened steel ball loaded in contact with the specimen surfaces. The materials investigated were three titanium alloys, Ti-6Al-4V (IMI 318), Ti-4Al-4Mo-2Sn-0.5Si (IMI 550) and Ti-6Al-5Zr-0.25Mo-0.25Si (IMI 685) tested under conditions of varying tangential force but with constant amplitude.

Initial experiments were performed under dry, non-lubricated, conditions. Fretting wear was produced in the annular ring where slip was occurring, and fatigue cracks were generated at the slip/non-slip boundary at the two points of the circumference perpendicular to the fretting motion. Typical examples of fretting wear damage and fatigue cracks are shown. IMI 318 is most susceptible to the development of fatigue cracks and IMI 685 shows the least susceptibility.

The magnitude of the tangential force has an influence on the nature of the debris. At a high tangential force there is considerable transfer of iron to the specimen surface and the debris is thought to consist of a mixture of titanium and iron oxides, whereas at a low tangential force the debris is mainly titanium oxide.

Introduction

Any metal-to-metal contact which is subjected to vibration can suffer damage due to fretting corrosion. In many contacts which occur in engineering practice the normal load is distributed over a relatively large area, the apparent area of contact, although the real area of contact is initially much less. Examples of this type of contact are press or shrink-fitted hubs on shafts, and pinned or riveted joints. As fretting develops at the areas of real contact the attrition of the high spots and the genreation of debris causes the areas of damage to spread and coalesce so that it becomes quite widespread. In some instances, however, the contact is of a more concentrat-

---

*Present address: Department of Mechanical Engineering, Oita Technical College, Oita City, Japan

Table I

Mechanical properties of the three titanium alloys

	318	550	685
UTS MN/m^2	980	1124	1057
0.2% PS MN/m^2	911	1023	926
elongation %	18	16	11
reduction in area %	44	53	25
hardness VHN	365	361	369
impact strength Nm	10.4	22.5	6.0
Fatigue strength at 10^7 cycles MN/m^2	539	647	417

ed form. This was the case in the frequently quoted occurrence of fretting in the bearings of automobiles being transported from Detroit to the West Coast. The vibration resulted in severe fretting between the nominally stationary balls and races at the small areas of contact. The result was a series of small depressions due to wear which resembled Brinell impressions and gave the name "false brinelling" to this type of fretting. The work described in this paper is confined to this type of contact since it can also lead to the initiation of fatigue cracks particularly when the contact is hevily loaded. The materials chosen for investigation are three titanium alloys whose fretting fatigue behaviour has previously been determined (I). The investigation has also provided further informationon on the process of delamination as a contributory factor in fretting.

Experimental Procedure

I. Materials

The three titanium alloys were obtained in the form of drawn rod 9.5 mm in diameter. The heat treatments were as follows:

IMI 3I8 Ti-6Al-4V
annealed 700°C for 2h, air cooled
IMI 550 Ti-4Al-4Mo-2Sn-0.I5Si
solution heat-treated 900°C for 30 min, air cooled
aged 500°C 24 h, air cooled
IMI 685 Ti-6Al-5Zr-0.5Mo-0.25Si
solution heat-treated I050°C for 30 min, oil quenched
aged 500°C 24 h, air cooled.

The mechanical properties are given in Table I. Specimens 25×7×6 mm were ground from the bar stock and the largest face was polished to a mirror finish on a diamond impregnated wheel.

2. Testing machine

The machine has been described previously in Japanese publications (2) but not in English. The principle is shown in Fig.1. Two horizontal spur gears O and O' are loaded eccentrically with two equal sector-shaped weights G and G'. When the gears are rotated, inertia forces are generated in the Y direction. Those in the X direction cancel each other. The equipment is attached to a vertical bar LS. The upper member of the contact,a hardened steel ball, hardness 720 VHN and 19mm diameter,is attached to the bottom end of the bar,and rests on the specimen which is held rigidly in a vice. The normal load is applied to the top end of the bar by screw mechanism to prevent macro-slip between the two surfaces.

An alternating tangential force F is induced at the contact. The test machine is shown in Fig.2, and is driven by an electric motor and belt drove which allows the speed of rotation to be changed. The normal load is measured by means of strain gauges on the vertical bar. The amplitude of motion is controlled by means of two flat springs which restrain the movement of the vibrating part of the machine, and is determined by means of strain gauges attached to these springs.

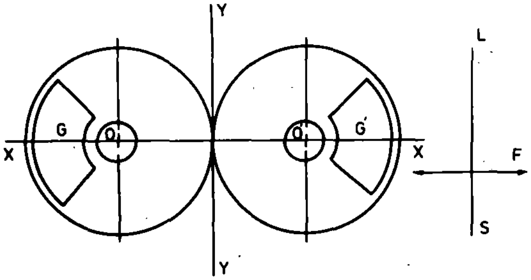

Fig. 1 The principle of the fretting machine. Rotating spur gears O and O' with out-of balance weights G and G'.

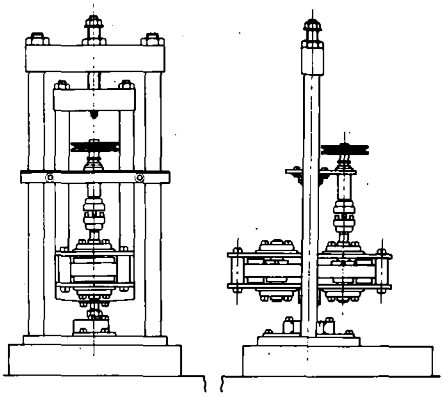

Fig. 2 Diagram of the fretting machine

The tangential force F depends on the mass of the out of balance weights and also on the speed of revolution,i.e.the frequency.

In the present work the weights were the same throughout and therefore the force was determined by the speed. The frequencies and associated values of F were as follows:

frequency	F
1300 rpm	1000 N
1100	500
800	250

The initial amplitude of slip was in all cases of the order of 20μm.

Results

The loads used were sufficiently high to produce plastic deformation of the specimen surface,resulting in a Brinell type impression. Fig.3 is an optical phtograph taken under oblique lighting showing a typical impression. The region of slip is therfore confined to a narrow annular ring at the periphery of the impression. In the initial experiments the normal load and tangential force were maintained constant at 7500 N and 500 N respectively but the number of cycles of fretting was varied between 1000 and 30 000. On ceasing the fretting a considerable amount of loose debris was found to have been generated and

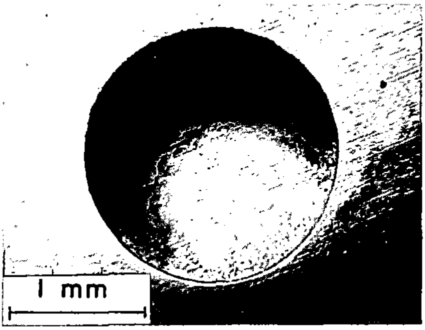

Fig.3 Optical photograph of Brinell impression in Ti-6Al-4V specimen. F=500 N, P=7500 N, 10000 cycles.

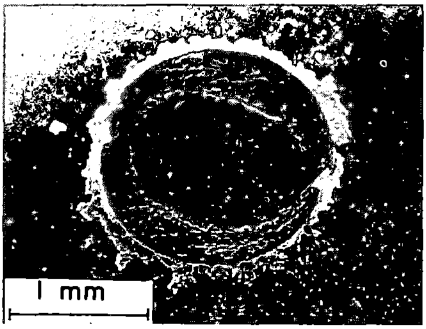

Fig.4 Ti-6Al-4V specimen after fretting, before ultrasonic cleaning. F=1000 N, P=5000 N, 10^6 cycles. Sliding direction vertical.

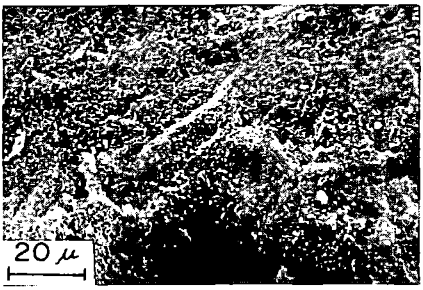

Fig.5 As Fig.4 showing debris particles.

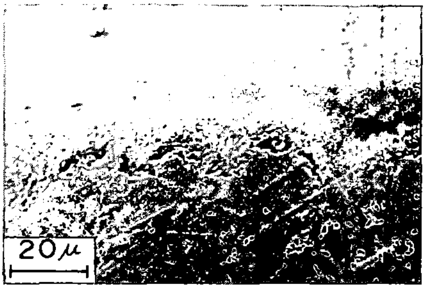

Fig.6 Ti-6Al-5Zr-0.25Mo-0.25Si after fretting and ultrasonically cleaning. F=500 N, P=7500 N, 1000 cycles.

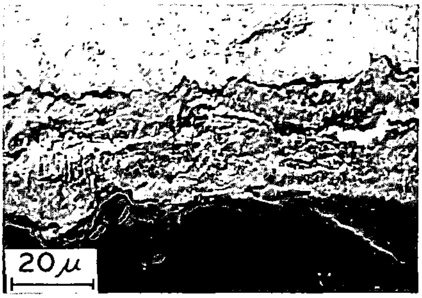

Fig.7 As Fig6, 5000 cycles.

Fig.8 As Fig.6 30000 cycles.

Fig.9 Ti-6Al-4V after fretting showing peripheral crack. F=500 N, P=7500 N, 1000 cycles.

Fig.10 As Fig.9, 30000 cycles. Fatigue cracks propagating from the fretted region.

Fig.11 Ti-6Al-5Zr-0.25Mo-0.25Si after fretting. F=500 N, P=7500 N, 300000 cycles. Fatigue crack propagating from the fretted region.

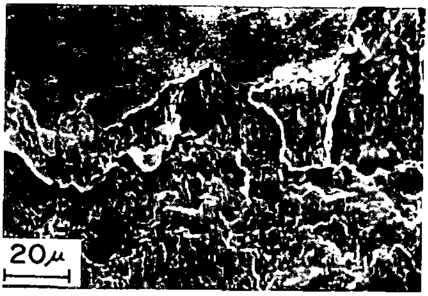

Fig.13 Ti-6Al-4V after fretting. F=1000 N, P=7500 N, 10^6 cycles. Severe damage and delamination.

extruded out of the contact. Figs. 4 and 5 show the appearance of the scr and debris on removing a specimen of Ti-6Al-4V from the machine which had experienced 10^6 cycles of fretting. The size of the debris is 2 μm and less. All the specimens were ultrasonically cleaned to remove the loose debris and examined in the Cambridge 600 Stereoscan scanning electron microscope.
On all three materials the annular ring of fretting damage incresed from isolated pits after 1000 cycles to become a continuous band of damage as the number of cycles rose to 30000 cycles. Figs.6,7 and 8 show this progression on IMI 685. After 5000 cycles there is evidence of compacted debris towards the outer edge of the contact and delamination at the inner edge, Fig.7. The damage develops more rapidly on IMI 318. After only 1000 cycles the individual pits have joined up to give the appearance of a continuous peripheral crack, Fig.9 and after 30000 cycles several fatigue cracks are observed propagating out of the fretting region,Fig.10. Fig.11 shows a fatigue crack propagating from the damaged area on IMI 685 after 300000 cycles.

A survey was made on the number of propagating fatigue cracks at each stage of fretting on the three materials and the results are shown graphically in Fig.12. A significant number of cracks has been initiated in IMI 318 after only 1000cycles whereas cracks are only initiated in IMI 550 and IMI 685 after

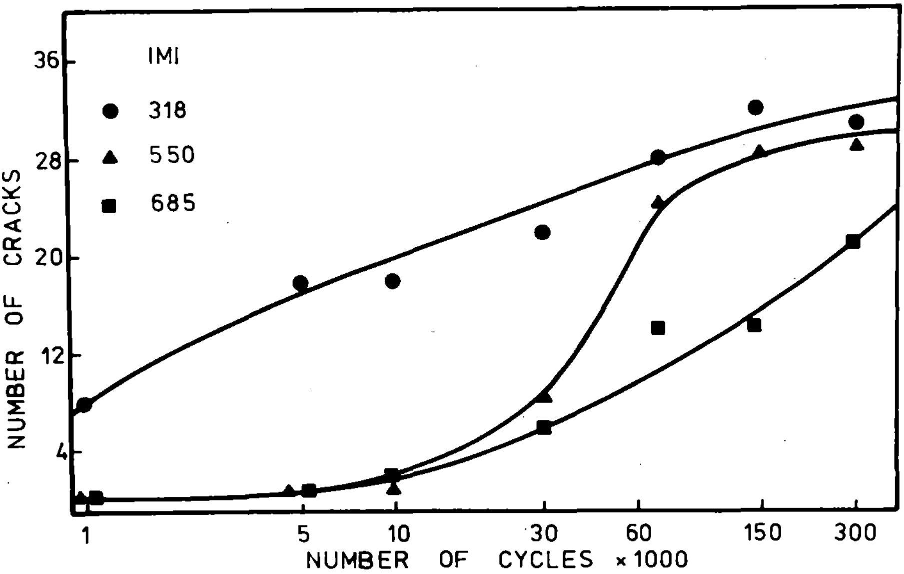

Fig. 12 Development of fatigue cracks after fretting in the three titanium Alloys.

10000 cycles.

The effect of varying the tangential force was studied on the alloy IMI 318. Doubling the tangential force from 500 to 1000 N greatly increased the surface damage and showed more evidence of delamination,Fig.13. The other effect of doubling the tangential force was to increase the amount of material transfer between the steel ball and the specimen surface and also to increase the pick-up of oxygen. This is shown in Fig.14 to 19. A marked decrease in titanium is also evident.

Discussion

There is ample evidence that the volume of fretting debris increases more or less linearly as fretting proceeds(3) This is reflected in the stereoscan pictures of the damage which is seen to increase in area as the number of cycles is increased. The more unusual observation is that the number of propagating fatigue cracks emanating from the fretted area is also increasing as the number of cycles is increased. The reason for fatigue cracks being seen in this case is that the normal load is so high that the alternating stresses in the material surrounding the contact area are sufficiently great to propagate the cracks generated by the fretting. It is a common experience to see cracks propagating from a contact where one of the members to the contact is being cyclically stressed. The three materials show different susceptibility to the initiation of fatigue cracks by fretting as shown Fig.12.
The information in Table II obtained from fretting fatigue studies on the same material used in the present tests confirms their different reactions to fretting. The determinations were made in rotating bending,i.e. zero mean stress, at a frequency of 25Hz. (1)(4). Although IMI 550 showed the greatest reduction in fatigue strength due to fretting it must be remembered that fatigue failure involves both initiation and propagation of a fatigue crack whereas fretting is mainly concerned with initiation only.

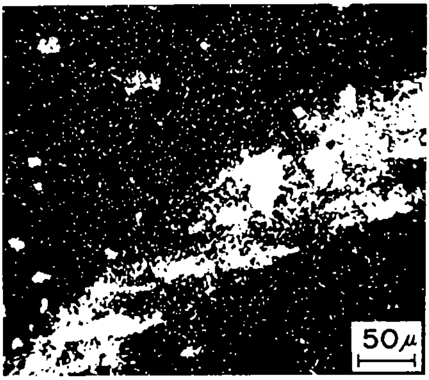

Fig.14 Distribution of Fe on fretted Ti-6Al-4V. F=500 N, P=7500 N, 10^6 cycles.

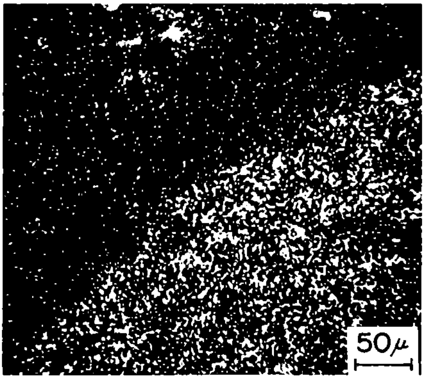

Fig.15 As Fig.14, distribution of O.

Fig.16 As Fig.14 distribution of Ti.

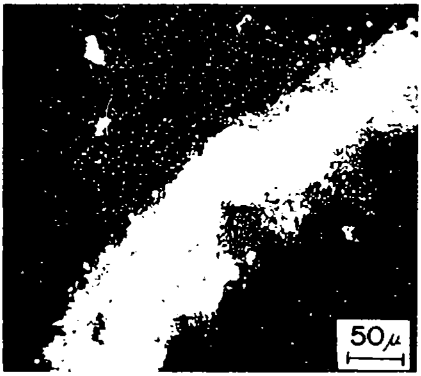

Fig.17 Distribution of Fe on fretted Ti-6Al-4V. F=1000 N, P=7500 N, 10^6 cycles.

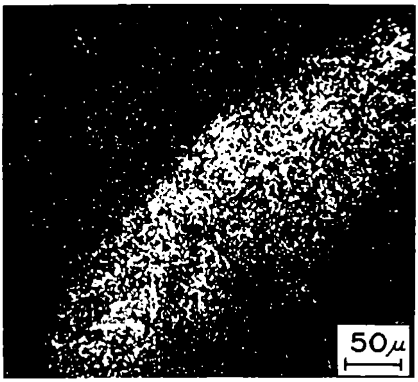

Fig.18 As Fig.17, distribution of O.

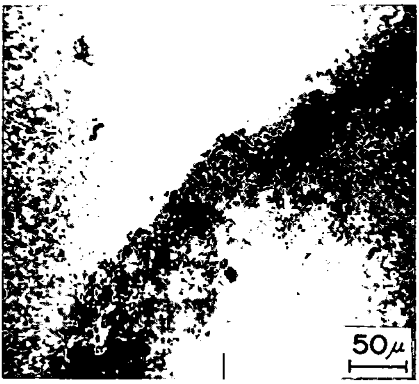

Fig.19 As Fig.17 distribution of Ti.

Table II

	318	550	685
Reduction in fatigue strength due to fretting (at 10^7 cycles) %	50	62.5	35
Number of fretting cycles to initiate a propagating fatigue crack at an alternating stress of ±278 MN/m^2	50 000	75 000	75 000
Proportion of total life spent in crack initiation at an alternating stress of ±278 MN/m^2, %	16	27	37

IMI 550 and 685 both required 50% more cycles to initiate a fatigue crack than IMI 318,and the proportion of the total life spent in initiating a fatigue crack was greatest in the case of IMI 685 and least in the case of IMI 318. The general conclusion is that IMI 685 is the most resistant and IMI 318 the least resistant to fretting fatigue.

In oxidising atmospheres the fretting debris is usually an oxide or oxides of the metals involved. In the present case iron is undoubtedly transferred to the titanium surface,whether as metallic iron which is subsequently oxidised or as compacted oxide debris is difficult to say from the X-ray analyses. The fact that the concentration of titanium is almost the same in the fretted area as outside when the tangential force is 500 N suggests that the debris is mainly oxides of titanium whereas at the higher tangential force of 1000 N there is considerable depletion of titanium suggesting that the debris has a much higher content of iron oxides.

Conclusion

Of the three titanium alloys tested, IMI 685 shows the greatest resistance to fatigue crack initiation by fretting, whereas IMI 318 shows the least resistance. This is in accord with previous work on the fretting fatigue behaviour of these alloys. Increasing the tangential load greatly increases the transfer of material between the surface and raises the iron oxide content of debris.

References

1. R.B.Waterhouse and M.H.Wharton, "The behaviour of three high-strength titanium alloys in fretting fatigue in a corrosive environment": Lubrication Engineering, 32, 1976, 294.
2. S.Goto, "Study on fretting corrosion of rolling bearing": Research Report of Oita Technical College, 6, 1969, 26.
3. R.B.Waterhouse, "Fretting Corrosion",:Pergamon, Oxford, 1972.
4. M.H.Wharton, "Environmental Effects in the Fretting of Titanium Alloys",: Ph.D. Thesis, University of Nottingham, (1977)