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Fatigue-crack initiation in IMI 829 caused by high-temperature fretting

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Fretting fatigue tests have been carried out on a recently developed near-α creep-resistant alloy, IMI 829. The fretting fatigue characteristics have been determined at temperatures of 400 and 600° C under conditions of high and low fatigue stresses. In each case fatigue-crack initiation has been examined and related to the fretting damage on the surface of the specimen, and the microstructure of the alloy.

1. Introduction

Over the last few years a new titanium alloy, IMI 829, has become commercially available. The alloy contains additions of Al, Sn, Zr, Nb, Mo and Si and has been designed to operate at temperatures up to 600° C. In particular, the excellent creep strength and metallurgical stability may enable the alloy to be considered for gas turbine discs and blades.

Extensive work has been carried out on the mechanical, creep and plain fatigue properties of the alloy, but nothing is known about its fretting fatigue characteristics. Titanium and its alloys are particularly susceptible to fretting damage and therefore it is essential that fretting fatigue data be acquired for this recently developed alloy. Furthermore, since the alloy has been developed for high-temperature service the data need to be obtained at elevated temperatures.

Recent work [1, 2] on Ti–6Al–4V has shown that fretting at ambient temperatures produces adhesion between the fretting surfaces, but at higher temperatures (400 to 600° C) a glaze-like oxide film can be produced on the fretted surface. This glaze-oxide is similar to that produced during the fretting of nickel-based alloys [3] but in Ti–6Al–4V it did not improve the fretting fatigue properties.

The object of the present work has been to determine whether similar fretting oxide/damage is produced on the surface of IMI 829 and to relate this to fatigue-crack initiation in the alloy. Correlations have also been sought between the nature of fatigue-crack initiation and the microstructure of this near-α alloy.

2. Experimental details

All the work described in the present paper has been carried out on a near-α alloy, IMI 829, which has the composition (wt %) Ti–5.5Al–3.5Sn–3.0Zr–1.0Nb–0.25Mo–0.3Si. The alloy was fully heat-treated by cooling from 1050° C (i.e. from above the β transus) followed by annealing 2 h at 625° C. This produced a uniform β grain size containing colonies of aligned α-platelets, the mean size of the colonies being 0.1 mm (Fig. 1). The mechanical properties of the alloy in this heat-treated condition are given in Table I for various test temperatures.

The fretting fatigue tests were performed under axial fluctuating tension. A detailed description of the experimental rig used and testing conditions have been described elsewhere [1]. Briefly, the fatigue specimen had parallel flats machined on its surface and fretting was induced by clamping a pair of bridges on to the parallel flats. The bridges were of the same material as the fatigue specimens and had been given the same heat-treatment. The specimen and bridges were surrounded by a small electrical furnace and tests conducted at 400 and 600° C. All tests described in the present paper were carried out with a superimposed mean tensile stress of 280 MPa, a contact pressure between bridges and specimen of 32 MPa, and the fatigue stress was applied with a frequency of 50 Hz. The test atmosphere was laboratory air

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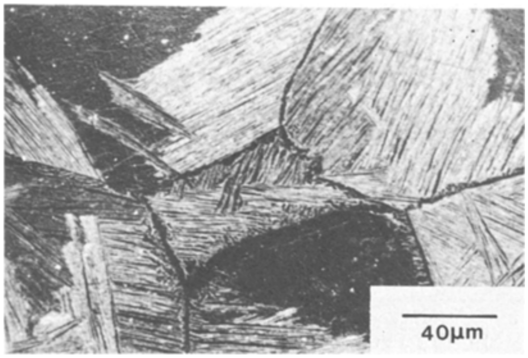

Figure 1 Microstructure of the alloy used in the investigation, showing colonies of aligned α-platelets.

with a relative humidity that varied between 50 and 65 %.

3. Results

3.1. Fretting fatigue curves

Fretting fatigue curves have been determined at 400 and 600° C and the detailed results are being published elsewhere [4]. Two specimens at each test temperature have been selected for detailed examination; one representative of a high-stress/short fatigue-life situation, and the other a low stress/long fatigue-life condition. The test conditions for each specimen are given in Table II.

3.2. General observations on failed specimens

Under all test conditions used in the present work, fatigue cracks were initiated at the surface of the specimen and these cracks propagated over about half of the specimen section before final, catastrophic failure. The general characteristic of all the fatigue fracture surfaces was one of extreme irregularity, indicating a very tortuous crack path. The faceted nature of the crack surface indicates that at both temperatures (400, 600° C) and at high and low stress the fatigue crack is following specific crystallographic planes. Similar observations have been made on the fracture surfaces of other titanium alloys fatigue tested at room temperature [5].

3.3. Fretting fatigue at 400° C; low fatigue stress

The scar areas on the surface of the specimens that have been subjected to fretting are composed of long parallel grooves (Fig. 2). Adhesion and material transfer between specimen and the foot of the fretting bridge were also observed in areas near to the final fracture (Fig. 3).

Considerable amounts of oxide are continually generated during the fretting fatigue tests at these elevated temperatures. In particular, the oxide formation takes place in the mouths of freshly produced fatigue cracks thereby leading to a wedging action which assists crack propagation (Fig. 4).

The fretting fatigue cracks invariably started at the edge of the fretting scar, and were observed to propagate into the specimen at a very steep angle, i.e. near to 90° to the surface rather than the more usual 45° (Fig. 5). Careful sectioning through the scar region showed that the initial stages of the fretting fatigue crack either propagated in a direction parallel to the boundaries of the α-platelets (Fig. 6) or alternatively propagated across the α-platelets (Fig. 7). The actual mode of crack propagation appears to depend on the angle that the α-platelets make with the specimen surface, e.g. if the platelets are orientated so that the fatigue crack cannot initiate and grow across the plates (i.e. platelets perpendicular to surface), then the crack will grow parallel to the α boundaries.

3.4. Fretting fatigue at 400° C; high fatigue stress

Fretting at 400° C under high fatigue stress produces a contact surface that is now considerably rougher (Fig. 8) indicating more adhesion and

TABLE I Mechanical properties of titanium alloy IMI 829

	0.2% Proof stress (MPa)	Tensile strength (MPa)	Elongation (%)	Notched tensile strength, $K_t = 3$ (MPa)
Tensile Properties, 20° C	840	955	9	1280
200° C	770	630	10	
400° C	640	520	10	
500° C	605	500	10	
600° C	525	425	13	
Creep properties (540° C)	Less than 0.1% total plastic strain in 100 h with a stress of 300 MPa.			

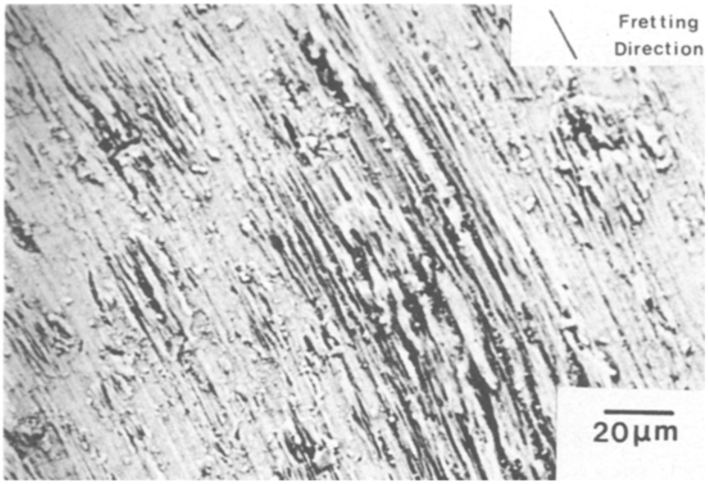

Figure 2 Fretting scar area on specimen tested at 400° C (low fatigue stress) showing long parallel grooves.

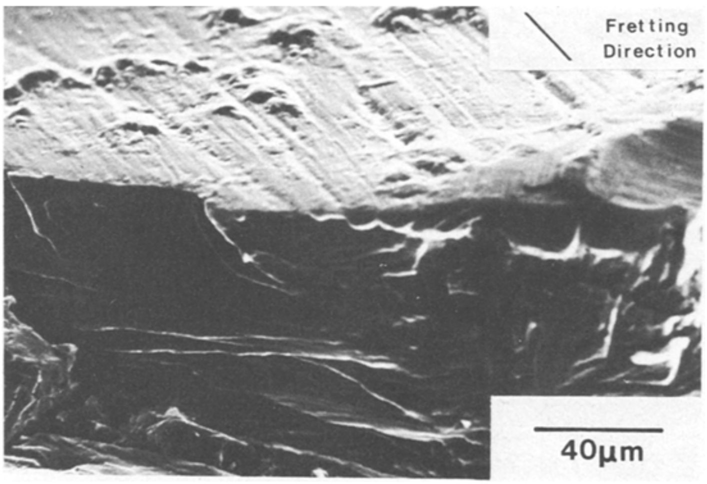

Figure 3 Adhesion and material transfer in regions close to the final fracture. Tested at 400° C; low fatigue stress.

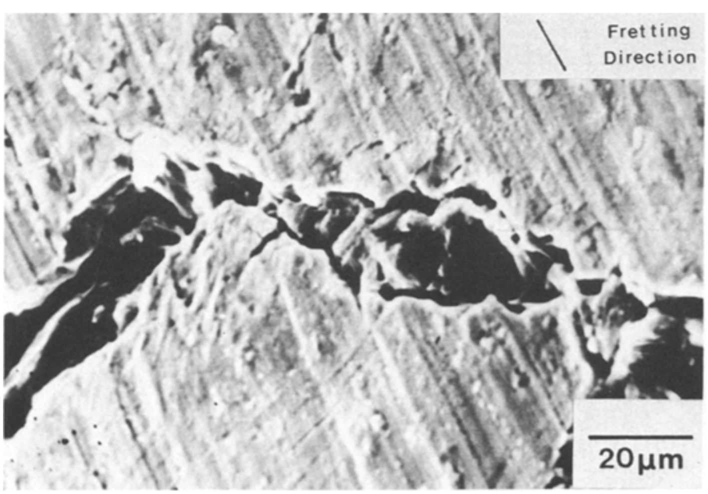

Figure 4 Oxide produced in the mouths of freshly produced fatigue cracks in the fretted area. Tested at 400° C; low fatigue stress.

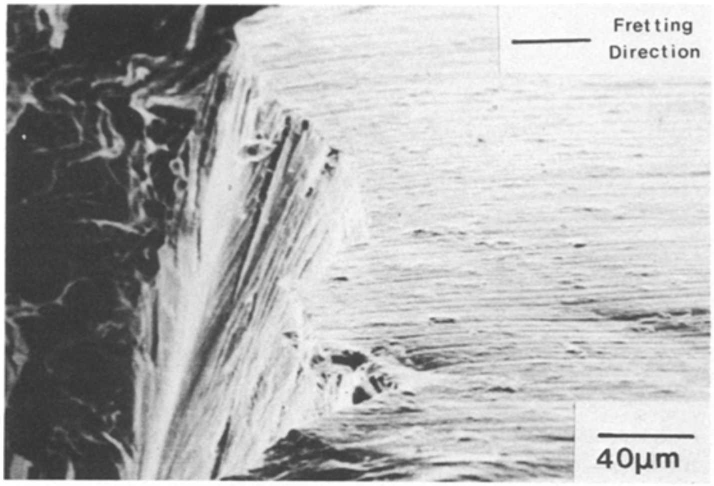

Figure 5 Fatigue crack propagating from the surface at a very steep angle. Tested at 400° C; low fatigue stress.

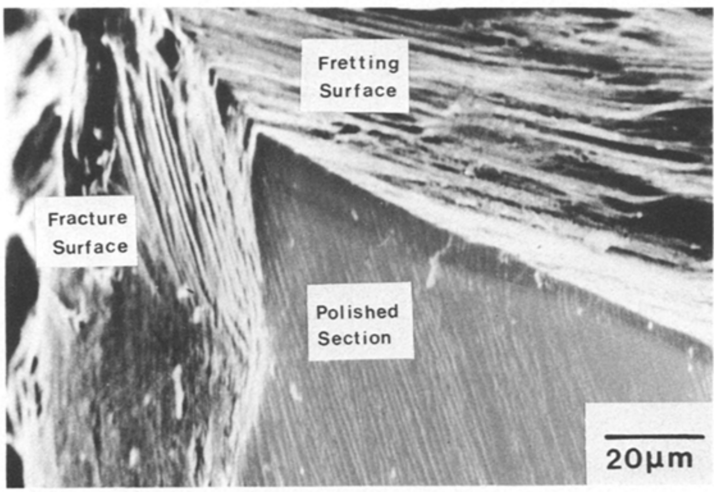

Figure 6 Fretting fatigue cracking initiating and propagating parallel to the boundaries of the α-platelets. Tested at 400° C, low fatigue stress.

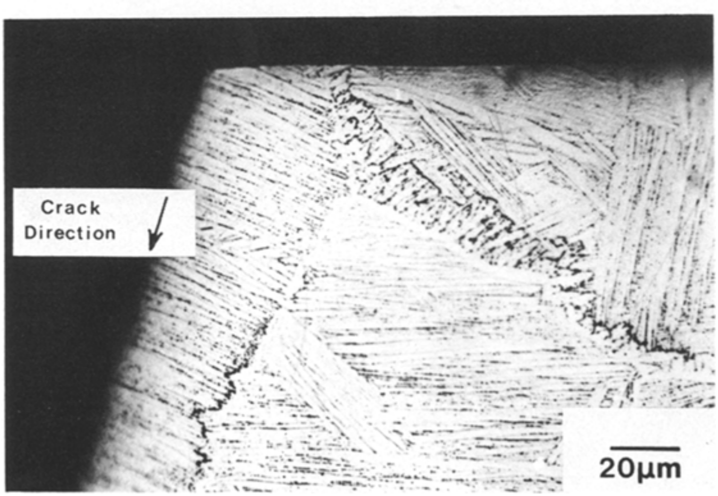

Figure 7 Fretting fatigue crack initiating and propagating across the boundaries of the α-platelets. Tested at 400° C, low fatigue stress.

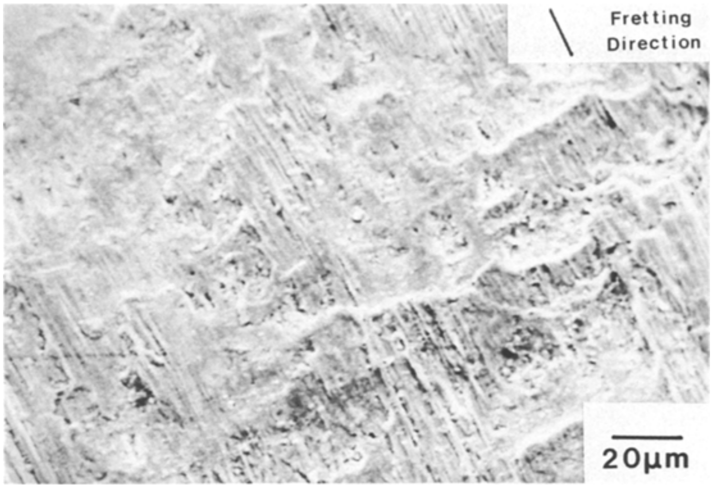

Figure 8 Fretting scar region of sample tested at 400° C under conditions of high fatigue stress.

material transfer between specimen and bridge foot.

The direction of the fatigue crack in the early stages of its propagation still follows a very steep angle to the specimen surface. At these higher stresses the crack propagates either along α-colony boundaries or across the α-platelets.

3.5. Fretting fatigue at 600° C; low fatigue stress

At the higher test temperatures a glaze-type oxide was observed in other titanium- and nickel-based alloys fretted at high temperatures. There was some evidence that this glaze-type oxide existed in the 400° C tests but was not so well developed. Owing to creep deformation of the substrate metal, at long test times this oxide was cracked in a direction perpendicular to the applied fatigue stress (Fig. 9). Initially the cracks in the oxide are small, parallel to one another and uniformly spaced. However, with further creep deformation the oxide cracks link together to form a macrocrack, from which fatigue cracks can nucleate (Fig. 10). Cross-sections taken through the cracked oxide show how the cracks impinge into the metal substrate (Fig. 11) thus acting as severe stress raisers. A particularly active site for this type of stress raiser to develop appears to be down prior β-grain boundaries (Fig. 12).

Once the stress raisers are present, fatigue cracking gets under way and at these high temperatures (600° C) the overall direction of the initial crack is approximately 45° to the surface of the specimen. Crack propagation on a microscale is still across α-platelets or parallel to α-boundaries (Fig. 13) and this can produce a characteristic stepped appearance to the 45° fracture (Fig. 14). In extreme cases the crack can

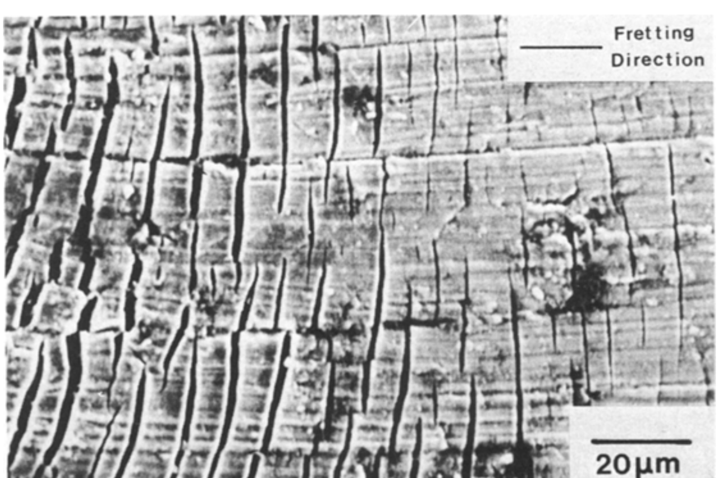

Figure 9 Cracking of the glaze oxide in a direction prependicular to the applied fatigue stress. Test temperature 600° C; low fatigue stress.

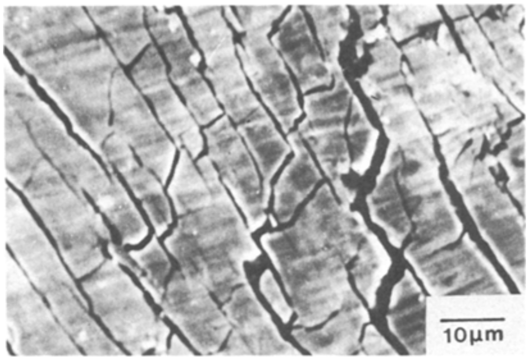

Figure 10 Microcracks in the oxide linking together to form a macrocrack. Test temperature 600° C; low fatigue stress.

propagate for large distances across the α-plates producing what appears at first sight to be gross delamination (Fig. 15) but what in reality is simply the crack favouring the cross-platelet path and therefore propagating in a direction parallel to the specimen surface.

3.6. Fretting fatigue at 600° C; high fatigue stress

In the fretting scar region some cracking of the oxide due to creep of the substrate is again in evidence, but at these higher fatigue stress levels delamination of the oxide is also occurring (Fig. 16). Furthermore the fatigue cracks are initiating at these delaminated regions (Fig. 17).

At these high temperatures and stresses considerable amounts of plastic deformation are taking place in the specimen substrate below the fretting bridge foot. This plastic deformation causes large shear stresses to develop in the metal substrate below the fretting scar, resulting in the fatigue crack growing at approximately 45° to the surface (Fig. 18). At these high temperatures and stresses the growth direction appears to be quite independent of the position and orientation of the α-platelets.

Once out of the influence of the fretting (shear) stresses the crack moves onto a plane at approximately 90° to the applied fatigue stress and here the crack now grows almost exclusively across the α-platelets. Since the orienation of the α-platelets changes from colony to colony across the specimen, this results in a very faceted type of fracture surface.

4. Discussion

The data presented in Table II shows the fretting fatigue properties of IMI 829 to improve as the test temperature is raised from 400 to 600° C. For an alternating stress of 110 MPa the fretting fatigue life is increased from 4×10^5 cycles at 400° C to 1.5×10^6 cycles at 600° C. The major cause of this improvement is the substantial development of the glaze-type oxide at the higher temperature which prevents, or delays, the normal type of surface damage that leads to the initiation of fatigue cracks in the presence of fretting. At the lower temperature (400° C) considerably more adhesion takes place between the fretting surfaces, producing roughening and ultimately fatigue-crack initiation. A further, though less important, effect at 400° C is oxide formation in the mouths of freshly formed fatigue cracks (Fig. 4) which will provide a wedging action and thus assist fatigue-crack propagation. At 600° C the oxide

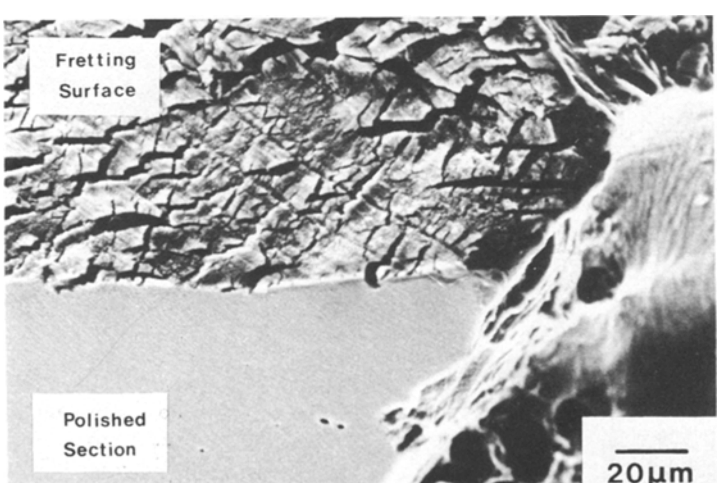

Figure 11 Cross-section through fretting scar with cracked oxide showing how crack extends into metal substrate. Test temperature 600° C; low fatigue stress.

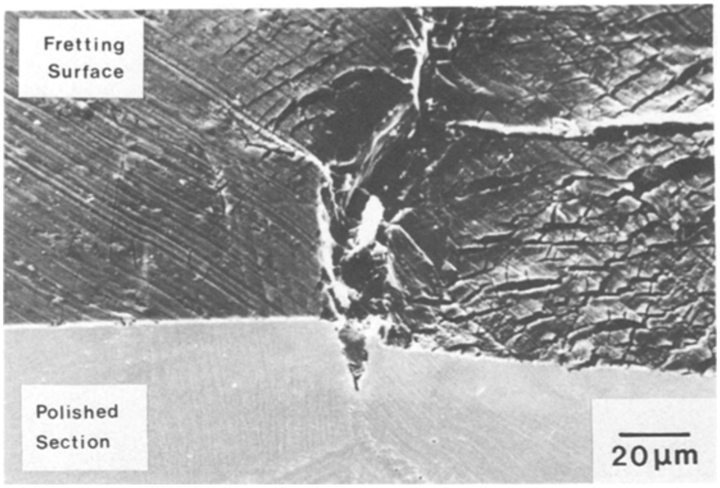

Figure 12 Crack developing down a prior β-grain boundary. Test temperature 600° C; low fatigue stress.

TABLE II Test conditions of specimens subjected to detailed examination

Test temperature (°C)	Fatigue stress (MPa)	Mean tensile stress (MPa)	Cycles to failure
400	86	280	2 522 000
400	110	280	393 000
600	110	280	1 454 000
600	129	280	259 000

will be more plastic and such wedging effects will assume less importance.

Although the fretting fatigue properties of IMI 829 at 600° C are superior to those at 400° C at all stress levels, the mechanism of crack initiation at 600° C appears to be different at high and low stress levels. At high stresses delamination is occurring producing roughening of the surface from which fatigue cracks grow. At lower stresses creep of the metal substrate is causing cracking of the oxide, thus producing severe stress raisers which initiate the fatigue cracks. It is likely that both these effects are taking place and competing with each other at both high and low stress levels. At the low stresses extensive delamination is not favoured so that over long periods of time the creep strain accumulates and eventually causes the glaze-oxide to crack. At higher stresses cracking due to creep is still occurring but the delamination process is the more damaging so that fatigue-crack initiation is from these latter sites.

The initial direction of the fretting fatigue crack is of some interest in this alloy system since it can be related directly to the microstructure, i.e. the colonies of aligned α-platelets. In very many alloy systems the fretting fatigue crack initially grows in a direction approximately 45° to the surface due to the influence of the fretting

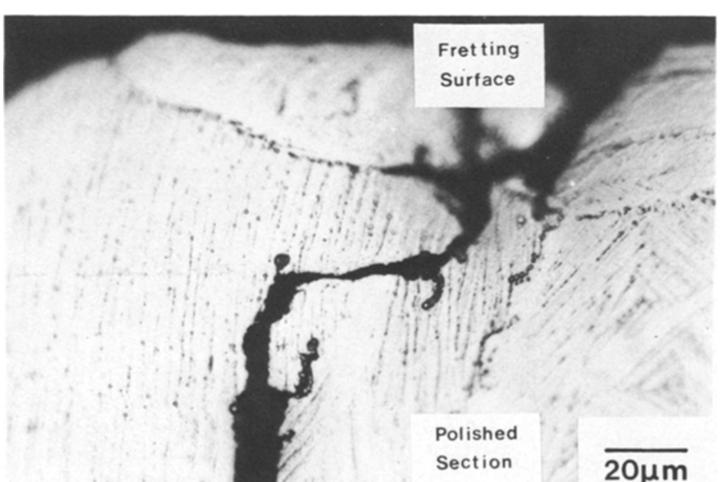

Figure 13 Fatigue-crack initiation site in sample tested at 600° C at a low fatigue stress. Propagation has started at a stress raiser at a prior β-grain boundary and then the crack has moved either across α-platelets or along α-boundaries.

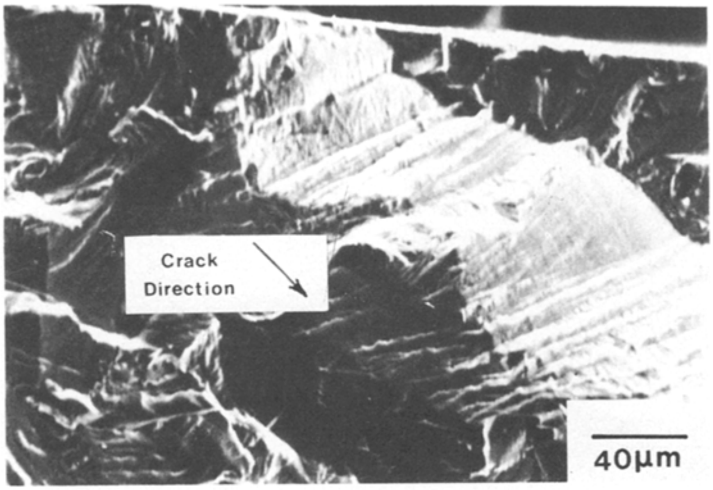

Figure 14 Characteristic stepped appearance to the initial 45° fracture due to the crack propagating across α-platelets and then along α-boundaries. Test temperature 600° C; low fatigue stress.

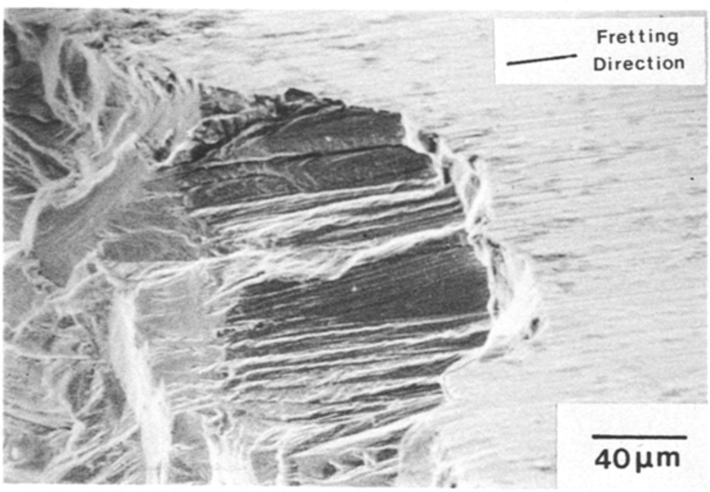

Figure 15 Crack propagation in a direction parallel to the surface of the specimen. Test temperature 600° C; low fatigue stress.

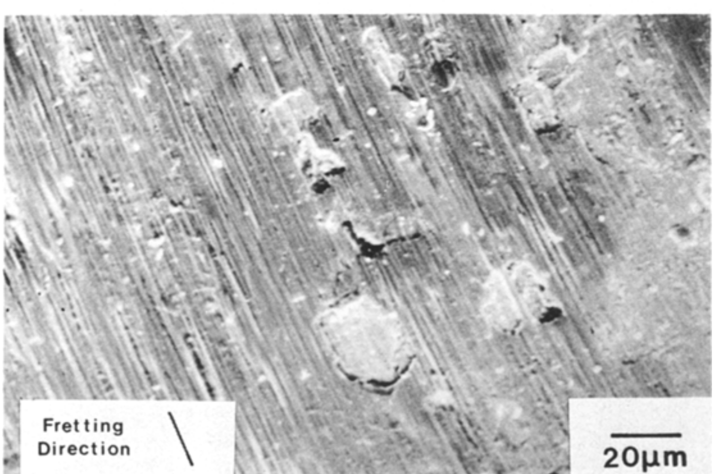

Figure 16 Delamination of the oxide in the fretting scar. Test temperature 600° C; high fatigue stress.

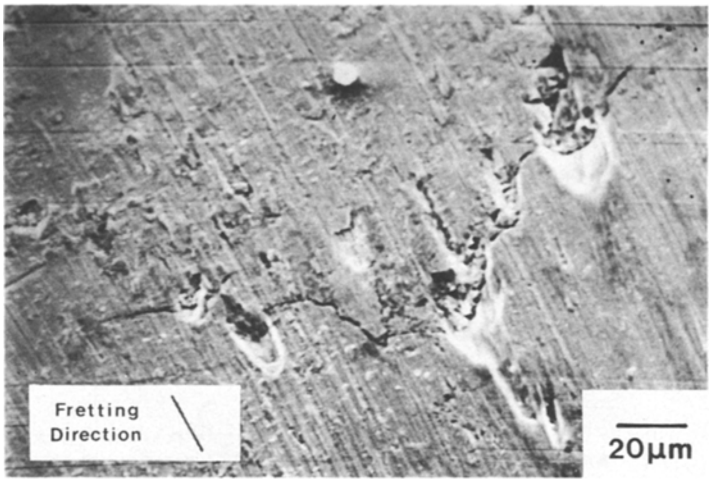

Figure 17 Initiation of fatigue crack at the delaminated regions. Test temperature 600° C; high fatigue stress.

shear stresses that act in the surface layers. This situation was observed to occur in the present alloy system when tested at 600° C. The high ductility of the alloy at this temperature has allowed the initial fretting fatigue crack to grow at an angle of 45° to the surface and, at high stress levels, this direction appears to be quite independent of the orientation of the α-platelets.

At the lower levels of fatigue stress the initial crack direction at 600° C is still at 45° but in many instances it takes on a stepped appearance where the crack has propagated alternatively across α-platelets and then parallel to α-boundaries (Fig. 14). In these near-α titanium alloys slip normally takes place on $\{0001\}$ basal and $\{10\bar{1}0\}$ prismatic planes of the α-phase. Since the fretting stresses induce shear stresses into the specimen surface, intense slip would therefore be expected to occur along the $\{0001\}$ and $\{10\bar{1}0\}$ α planes. The α-platelets are aligned with their c-axis parallel to the long axis of the platelet and therefore the potential slip planes of the alloy lie perpendicular and parallel to the α-platelets. In the early stages of fretting the fatigue crack is observed to propagate across the α-platelets and parallel to the α-boundaries, i.e. fatigue cracking is taking place largely along the shear planes of the alloy.

The presence of the glaze-oxide on the surface might be expected to reduce the coefficient of friction and so reduce the induced shear stresses at the surface which would then oppose the 45° crack growth that is observed to occur at 600° C. However, measurements made on a Ti–6Al–4V alloy at elevated temperatures [2] show that the coefficient of friction under fretting conditions at 600° C is around 0.6 and much higher than the coefficient at 400° C. It appears likely that the same situation exists in the present alloy and

Figure 18 Fatigue crack initiation and growth at 45° to the surface of the specimen. Test temperature 600° C; high fatigue stress.

therefore substantial shear stresses will be induced into the surface during the 600° C test, thereby encouraging the 45° crack growth.

Tests undertaken at 400° C show different behaviour in that the initial direction of the fretting fatigue crack is now at a steep angle to the specimen surface (Fig. 5). In all tests at 400° C careful sectioning through the scar region showed the initial stages of the fatigue crack to be always closely associated with the α-platelets. The preferred crack growth direction was across the α-platelets but propagation was also observed along or parallel to the boundaries of the α-platelets. This strong dependence of crack initiation on microstructure is probably due to a lower ductility of the alloy at 400° C (compared to 600° C) and a reduced coefficient of friction [2] which will have the effect of decreasing the magnitude of the shear stresses induced into the surface layers. This will inhibit 45° cracking, though the crack path is still along the shear planes of the alloy.

Further work needs to be undertaken on the fretting fatigue behaviour of this IMI 829 alloy before its regular use in situations where fretting can occur. The present work has shown that the fretting fatigue characteristics are closely related to the microstructure of the alloy and to the formation and breakdown of a surface oxide film. Since the fretting fatigue properties are allied to the orientation of the α-platelets in the colonies, it would be of importance to determine the fretting properties of the same alloy heat-treated to produce a basket-weave α-structure rather than the colonies of aligned α-plates. In this respect, work on other titanium alloys [6] has shown the basket-weave microstructure to be more resistant to the initiation of fatigue cracks by fretting. Further work is also required on the conditions under which the glaze-oxide film can form and break down under fretting conditions. Generally the fretting properties are improved when a glaze oxide is developed and therefore attention should be given to modifying the surface of IMI 829 to produce a better developed glaze oxide, perhaps by ion-implantation.

5. Conclusions

(1) The fretting fatigue properties of IMI 829 improve as the temperature of testing is raised from 400 to 600° C.

(2) At 400° C the initial fretting fatigue-crack direction is at a very steep angle to the surface, and the crack is initiated at the roughened surface caused by adhesion during fretting.

(3) At 600° C the initial fatigue-crack direction is at approximately 45° to the surface, and the fatigue crack is initiated at cracks in the oxide that have been formed as a result of creep of the metal substrate.

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