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The Influence of Fretting on Fatigue

by
W. J. Harris

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THE INFLUENCE OF FRETTING ON FATIGUE

by

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SUMMARY

A recapitulation of the characteristics of the fretting fatigue phenomenon described in AGARD Advisory Report No.8, with a re-appraisal of the theory of the basic mechanism in the light of recent research, tend to confirm:-

1. the significance of the residual tensile stress field remanent after plastic compression of the asperities,

2. the analysis of the fatigue results indicating that, the sensitivity of fretting fatigue to the contact pressure is similar to the 'notch sensitivity' of the material,

3. by microscopical studies, the nucleation of fretting fatigue cracks near the plastic zones surrounding the scars and, their propagation along 45° planes rather than normal to the fatigue stress axis,

4. that the modest target of achieving "anti-fret" resistance up to 150°C (suitable for Mach 2.2 civil aircraft) can be met by the use of "cured" polymeric – MoS_2 films interposed between the contact faces.

RESUME

Le rappel des caractéristiques du phénomène de la fatigue par frottement décrit dans l'Advisory Report No.8 de l'AGARD, et une nouvelle appréciation, à la lumière des dernières recherches, de la théorie du processus de base semblent confirmer:

1. l'importance du champ résiduel d'efforts de traction rémanent après la compression plastique des aspérités;

2. l'analyse des résultats concernant la fatigue, indiquant que la sensibilité de la fatigue par frottement à la pression de contact est pareille à la sensibilité à l'entaille du matériau;

3. à la suite d'études au microscope, que les fissures dues à la fatigue par frottement se forment en noyau au voisinage des zones plastiques qui entourent les marques, et qu'elles se propagent suivant des plans de 45°, et non pas normalement à l'axe de l'effort de fatigue;

4. que l'objectif modeste que l'on s'est fixé de réaliser une résistance au frottement pour les températures allant jusqu'à 150°C (convenant aux avions de transport civil volant à M = 2,2) peut être atteint en faisant interposer entre les faces de contact des couches polymériques – MoS_2 "traitées".

CONTENTS

THE INFLUENCE OF FRETTING ON FATIGUE

W. J. Harris

1. RECAPITULATION

At the Turin Structures and Materials Panel Meeting in April 1967, the first report on "The Influence of Fretting on Fatigue" was presented and later published as AGARD Advisory Report No. 8.

Hereafter, the researches on fretting fatigue reported refer essentially to:-

1.1 experiments designed to elucidate some of the theoretical aspects of the fretting fatigue mechanism discussed in AGARD Advisory Report No. 8 and,

1.2 the evaluation of certain "anti-fret" techniques suitable for operation at temperatures from ambient to 150°C.

Some recapitulation of the experimental evidence and the general ideas concerning the fretting fatigue phenomenon, would seem to be instructive whilst maintaining continuity. Accordingly, many of the characteristics of the fretting fatigue phenomenon can be identified in the complex interplay of joint elements under dynamic loading.

Thus for example, in:-

1.3 The Fatigue of Structures

Herein, many authorities have demonstrated that the high strength reduction factors typical of long life fabricated structures can be attributable, only in part, to the stress concentration features of the design; in fact, strength reduction factors, as high as 8 to 10, can be correlated with the intrusion of fretting fatigue to a marked degree.

Thus it transpires that the "Mean Structure Curves" as proposed by Heywood et al.[1] resemble, in form and magnitude, in the long endurance region, the fretting fatigue curve for the corresponding materials.

1.4 Crack Propagation

The author[2], and Frost et al.[3] have shown that for relatively short cracks, the rate of crack propagation is proportional to the cube of the effective fatigue stress; furthermore, there is a lower limiting or, threshold stress, below which cracks will not propagate and so define "non-propagating cracks". A logical deduction from the previous observations would be to identify such "threshold stresses" with the "fretting fatigue limits" given by the "Mean Structures Curve": all the experimental evidence tends to support this deduction.

1.5 Friction and Wear

Several interesting quantitative theories of friction and wear have, in effect, involved the fatigue phenomenon, placing great emphasis on the surface tensile stress which follows in the immediate wake of the sliding contact; the work of Kraghelsky and Nepomnyaschi[4] is noteworthy in this respect.

1.6 The "Asperity" Stress Fields

Some simple "Photo-elastic Stress Studies" reported in AGARD Advisory Report No. 8, demonstrated that, just outside the compression fretting pad, a surface tensile stress, approximately three times the nominal pad pressure, could be developed and, by implication, this order of stress concentration could arise between the "asperities" which have plastically yielded.

In anticipation of the latest theory of the basic mechanism of fretting fatigue proposed later in this report, with supporting experimental evidence, it will become apparent that the highest possible significance has been placed on the "Residual Stress Fields", particularly those of a tensile character, resident in the plastic zones surrounding the substrate material of the asperities.

1.7 The Nucleation of Fretting Fatigue Cracks

A study of the nucleation and propagation of fretting fatigue cracks has revealed two important characteristics, namely:-

(a) nucleation seems to occur with equal probability within the fretting scar or just outside the scar boundary,

(b) in the absence of fretting, fatigue initiation is predominantly normal to the principal fatigue stress direction (Stage II initiation) but, in the presence of fretting, fatigue initiation is substantially along planes oriented at 45^{o} to the fatigue stress axis. (Stage I initiation.) The dependence of Stage I initiation on residual stress fields has been well brought out in various papers[5,6,7] presented at the International Conference on Fracture held at Brighton, UK in April, 1969, and lends strong support to the thesis that, "fretting fatigue with Stage I initiation, is strongly controlled by the residual stress fields generated along the plastic peripheries of the asperities".

2. A RE-APPRAISAL OF BASIC MECHANISM THEORY

The theory of the mechanism of fretting fatigue, as developed herein, attaches high significance to the residual tensile stress fields generated by the plastic compression of the asperities: consequently, it is postulated, the major deleterious effect of fretting on fatigue strength can be attributed to the superimposition of the applied dynamic stresses on such residual mean tensile stresses. Of course, further loss of fatigue strength may result, due to wear and corrosion, depending on the interaction of the contacting metals with the environment.

2.1 Residual Stress Fields

The asperities of a compressed surface yield under a nominal applied pressure (p_0) to produce a real area of contact (A) when $p_0A_0 = Y_0A$ ($Y_0 \sim$ the "primitive" yield strength).

Furthermore, around the profiles of the plastic zones (the "plastic wedges" of Figure 6) there are generated compensating residual tensile stress fields which, very near the plastic profiles, attain values of the same order of magnitude as the Yield Strength. Thus, it is considered highly probable that the superposition of fatigue stress on the residual tensile stress field leads to the nucleation of fatigue cracks which propagate predominantly, along the "plastic wedge" and, hence, mainly on planes oriented 45^{o} to the surface of the fretted specimen.

The analogy between the "plastic wedge" theory of fretting fatigue and the influence of a cold working process such as "shot peening" is sufficiently close to warrant further examination. The influence of "shot peening" on the fatigue strength of metals may be conveniently summarized as follows:-

2.1.1 Marked improvements in bending and torsional fatigue can be produced by "shot peening" provided the specimen or component contains a "stress concentration" detail (a "notch") or, the material is in a "defective" state due to metallurgical processes (adverse thermal stresses: "decarburization": electrodeposited metals, etc.). Little, if any, measurable improvement results if the specimen, in the unpeened state, already exhibits a normal fatigue strength.

Furthermore, fatigue failures of "shot peened" metals initiate, mainly, from the surface and, substantially, along planes oriented at 45^{o} to the peened surfaces. Under conditions of "partial coverage", where the peened surface consists of discrete spherical cap indentations, fatigue cracks are known to initiate in the regions ("plastic profiles") surrounding the indentations with a significant lowering of the fatigue strength below the values characteristic of the unpeened state.

2.1.2 Fatigue tests performed under direct stress conditions do not usually show any improvements by "shot peening" and, more often than not, yield fatigue strength values lower than those for the unpeened state: in the latter case of pronounced fatigue damage by "shot peening", it has been shown that fatigue nucleation has occurred subcutaneously in the residual tensile stress field.

The analogy between the indentation produced by "shot peening" and the plasticly deformed asperities, typical of fretting, is indeed very close which, coupled with the experimental evidence of the conditions for Stage 1 initiation[5,6,7], lends confirmation to the implicit role of residual tensile stress fields in the fretting fatigue phenomenon.

2.2 Fretting Fatigue Damage

To a first approximation, it would appear logical to assume that fretting inflicts damage to fatigue similar in magnitude to that of an applied mean tensile stress of value Y_0. Since most of the experimental fatigue work described herein has used the repeated tensile mode of stressing $(0 - f)$ or $(f/2 \pm f/2)$ then, the magnitude of fretting damage may be conveyed by comparing, the unfretted fatigue strength f_0 with the "fretted" fatigue strength f_p, there being fatigue equivalence between $(f_0/2 \pm f_0/2)$ and $(f_p/2 + Y_0) \pm f_p/2$, which takes the form

$$(f_0/2U)^2 + (f_0/2\sigma_a)^2 = 1$$

$$[(f_p + 2Y_0)/2U]^2 + (f_p/2\sigma_a)^2 = 1 ,$$

where U = tensile strength

σ_a = the alternating fatigue strength

if the Gerber parabolic law is assumed to be applicable.

The above formulae do, of course, calculate the maximum fretting damage by virtue of the assumption that a steady mean tensile stress Y_0 operates throughout a significant test volume of material whereas, to be realistic, the probability of nucleation must be invoked which depends on the real area of the contacting asperities.

2.3 The Probability of Nucleation

Some early$_0$ work by the author[2] on "notch sensitivity" (η) in fatigue, may be brought to mind wherein the main thesis, "considered 'size effects' in fatigue as merely the expression of the probability of finding a 'characteristic flaw' in the length, area of volume of the material subjected to the fatigue stress".

This probability argument was then developed to show that

$$\eta = 1 - \exp(-\beta A/A_0) = 1 - \exp(-\beta p_0/Y_0) ,$$

where, $\sqrt{A_0}/\beta$ is proportional to the linear dimension of the "Characteristic Flaw". An interesting feature of this "notch sensitivity" interpretation was the logical development of a maximum K_f (Strength Reduction Factor) dividing the (K_f vs. K_t) field into the "Propagating" and "Non-propagating" species of fatigue cracks so that, in the case of fretting fatigue, it is possible to write:-

$$\eta = [f_0/f_p - 1]/[f_0/f_n - 1] = 1 - \exp(-\beta p_0/Y_0) ,$$

where, f_n is the repeated tensile "threshold stress" for "non-propagating cracks" and η and β are characteristics denoting the sensitivity of the alloy to fretting fatigue.

For most alloys, which strain harden considerably prior to fatigue nucleation, it is more realistic to replace Y_0 in the above formula with the tensile strength, as being the terminal value of the yield strength prior to fracture.

2.4 Crack Propagation

Frost[3] of the National Engineering Laboratory, Scotland has, for many years, been responsible for the brilliant experimental work concerned with the mechanism of the growth of fatigue cracks and his observations on fretting fatigue in particular are so relevant to the subject matter of this report as to merit quotation:-

> "Many fatigue failures in service are a result of cracks forming in areas where fretting has occurred. When two pieces of material, clamped together under a certain contact pressure transmit cyclic tangential stresses, the oxide layer on contacting asperities is destroyed and they weld together. Although the continual welding and breaking of contacting asperities produce debris which causes abrasive wear, fatigue cracks are found to form at the edges of the locally welded areas. Because surface cracks, can, under severe fretting conditions, form at nominal cyclic stresses insufficient to cause complete failure the fretting fatigue limit is governed by the cyclic stress necessary to propagate these cracks. For example, it is found that the fretting fatigue limits of various ferritic steels under the most severe fretting conditions are about the same, i.e., increasing the tensile strength of the steel does not result in a higher fretting fatigue limit than that obtained with the mild steel."

Thus the K_f (maximum) = f_0/f_n in the present notation, which define the conditions for non-propagating cracks, also define fretting fatigue limits (f_n) according to Frost and the author. It is also interesting to note that the fretting fatigue limits of alloys are sensibly the same as the base metal e.g., steels and iron: Nimonic alloys and nickel: Aluminium alloys and pure aluminium, etc.

There is a simple explanation for this rather surprising fact which, quite recently, has emerged from the author's crack propagation studies, viz: that, crack growth rates are proportional to the cube of the strain (and not stress) and non-propagating cracks, defined by zero rate, are characterised by a threshold strain, which is approximately 5×10^{-4} for repeated tensile stressing and 2.86×10^{-4} for alternating stressing.

3. THE EXPERIMENTAL RESULTS

3.1 Metallography

3.1.1 Electron Probe Micro-analysis and X-ray Diffraction

It was not possible to deduce quantitatively the composition of the fretting "scar" material, using the "Electron Probe" and X-ray diffraction techniques; approximately, titanium and oxygen were detected in equal proportions, with traces of aluminium and copper in the alloys IMI 318A and, IMI 230 respectively. One of the objects of this analytical work was to correlate the "temper colour" scale, determined for titanium alloys, with the effective temperatures generated during fretting but the specular reflection and interference colours produced by heating a polished specimen do not correspond with the optical characteristics of finely divided fretting debris, which behaves as an effective light scatterer.

3.1.2 Optical Microscopy

Optical microscopy studies of some tapered sections of the fretting fatigue cracks confirmed:-

3.1.2.1 the tendency for nucleation just outside the visible scar: furthermore, in the $(\alpha-\beta)$ structure of the (6 Al:4 V) alloy, cracks tend to avoid the β-phase but, where the resolved shear stress demands a frontal approach to the β-phase, the crack deviates to propagate along the $(\alpha-\beta)$ boundaries. This feature is already well known in the sense that the basic fatigue strength of $(\alpha-\beta)$ titanium alloys depends critically on the micro-structure (Figs.7,8,9),

3.1.2.2 the nucleation of 45^{0} cracks, along the 'plastic wedge' planes, under the asperity (Fig.10).

3.1.3 Scanning Electron Microscopy (SEM)

The topographical details of some of the fretting fatigue failures have been established using the 'Scanning Electron Microscope'. Again, the characteristic 45^{0} crack orientations have been confirmed together with the interesting feature of surface 'striations', the result of plastic deformation (Fig.11).

4. THE FRETTING FATIGUE RESEARCHES

4.1 Elevated Temperature Tests

In AGARD Advisory Report 8, consideration was given to the pre-requisites for an 'anti-fret' medium for use at elevated temperatures; such factors as chemical compatibility and, adequate rheological properties, among others, were considered. As regards the problems of fretting at elevated temperatures and, in particular, the immediate one in the range from ambient to 150°C, typical of Mach 2.2 civil transport aircraft, several promising avenues of research have been examined, based, essentially, on the application of solid lubricants, such as molybdenum disulphide (MoS_2), carried in a vehicle with the requisite rheological properties; in fact, the "anti-fret" primer LR.8123, which has proved extremely valuable for ambient temperatures, on primary spar structures, wing skin and pressure cabin faying surfaces, was a direct result of our fretting fatigue researches.

Unfortunately, in common with many other similar "primer" schemes examined, the rapid decrease of flow resistance in the range 80°C - 100°C, led to metallic contact through the "primer" with subsequent unacceptable fretting damage. Further work confirmed the importance of flow resistance at temperature and, in fact, MoS_2 in an epoxy resin vehicle, cured at 150°C, provides an excellent "anti-fret" medium for operation up to 150°C (Fig.5). No doubt, there are many elevated temperature curing polymers, which would work equally well at elevated temperatures.

In practice, there would be difficulties in curing large structural elements which had been treated with such anti-fret media and, the possibilities of curing polyester resins *in situ*, with radiation have been considered. However, our current efforts are directed toward the modification of some standard polymers with the object of increasing their flow resistance at elevated temperatures but, after room temperature curing only.

It may be noted that the use of materials such as "electro-deposited tin-nickel alloy" (a promising anti-fret scheme for titanium alloys) anodising of aluminium alloys: the majority of greases (MHT being an exception) and "loaded primer schemes", are inadequate for aluminium alloys operating around 150°C.

It has been demonstrated that "loaded polymers" offer a solution to the fretting problems up to 150°C, provided flow resistance can be markedly increased at elevated temperatures; this, necessitates further work on the various methods which are capable of accelerating polymerization *in situ*.

In the next phase of our fretting researches it is planned to:-

(1) consider the curing characteristics of polyester resins suitable for use up to 150°C,

(2) evaluate the effect of "flame sprayed" stainless steel loaded with sintered PTFE on aluminium alloys,

(3) develop suitable anodised films on titanium alloys subsequently loaded with various solid lubricants (e.g. molybdenum disulphide, boron nitride, silicon nitride, etc.), where the fretting fatigue investigations will cover the range, ambient to 500°C.

4.2 A Fretting Sensitivity Index

The author proposed earlier on that the relationship between f_0, f_p, and f_n, the unfretted, the fretted and the non-propagating fatigue strength values respectively and the applied nominal pressure (p_0) could be expressed in a revealing manner by defining a "Fretting Sensitivity Index" thus:

$$\eta = \frac{(f_0/f_p) - 1}{(f_0/f_n) - 1} ,$$

and on theoretical grounds that

$$\eta = (1 - \exp(-\gamma p_0) .$$

Whilst this formula gives extremely useful estimates of fretting fatigue strength, nevertheless, there is no obvious correlation of γ(Table I) and, static mechanical properties; in fact, γ, for the alloys tested, seems to reside in the range (0.13 to 0.22) and may, perhaps, if it is decided to ignore the special case of the clad aluminium alloy, be constant and independent of all other properties.

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*Papers presented at The International Conference on Fracture, Brighton, UK, April 1969.

TABLE I

Alloy	f_0	f_p (tons/in^2)	f_L	p_0	η	*Mean* γ
Nimonic 90 (Solutionised)	21.0	21.0	6.7	0,0.25	0	0.132
	21.0	12.6	6.7	2.0	0.313	
	21.0	9.7	6.7	6.0	0.548	
	21.0	7.8	6.7	12.0	0.798	
Nimonic 90 (Solutionised and Precipitated)	19.5	7.8	6.7	12.0	0.790	0.130
IMI 318A	46.0	9.0	3.35	6.0	0.585	0.147
IMI 230	26.0	9.0	3.35	6.0	0.553	0.135
DTD 5070A (at 150°C)	4.53	2.05	1.295	3.0	0.483	0.220

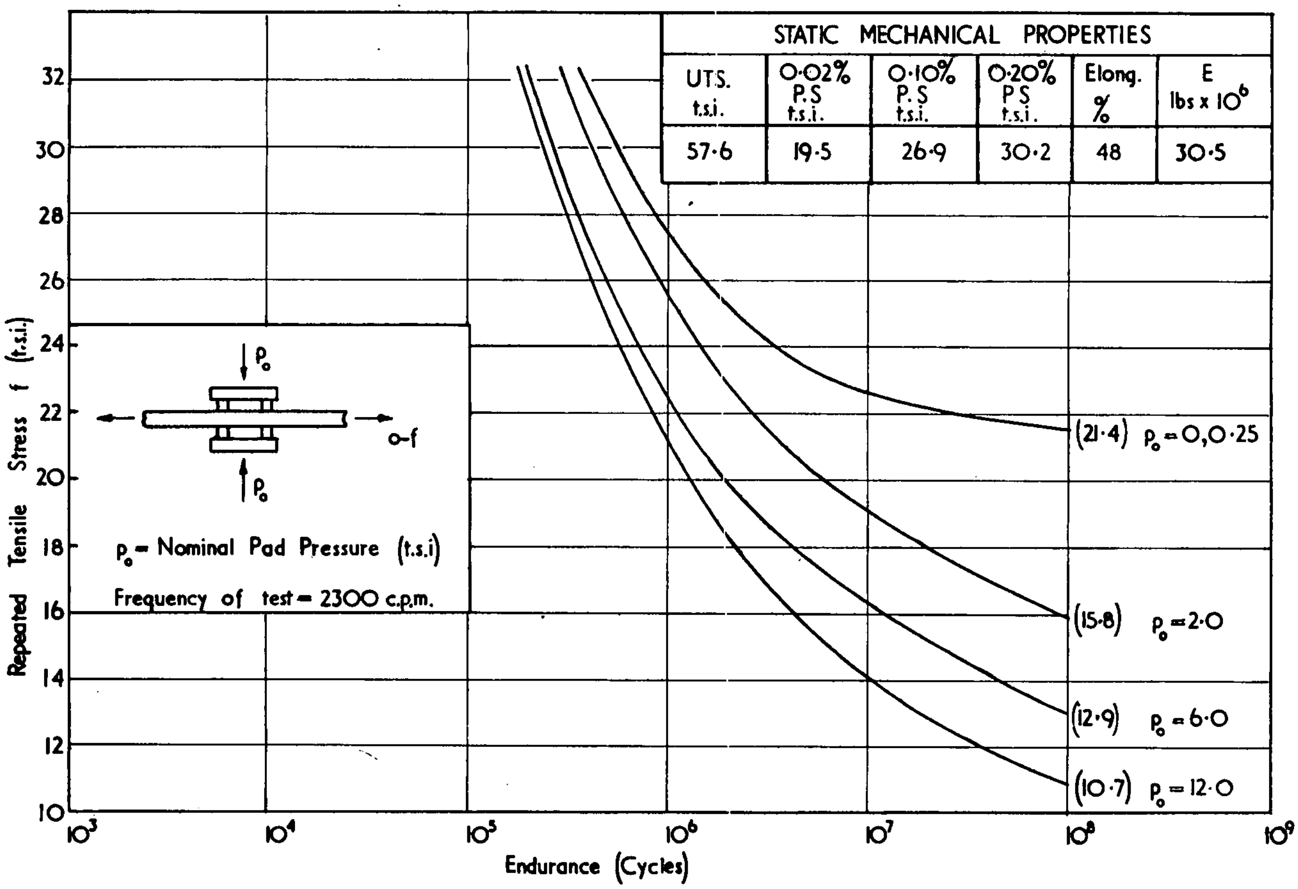

Fig.1 Fretting fatigue. Nimonic 90 alloy (58% Ni: 20% Cr: 18% Co: 2.5% Ti: 1.5% Al), solution treated 1080°C

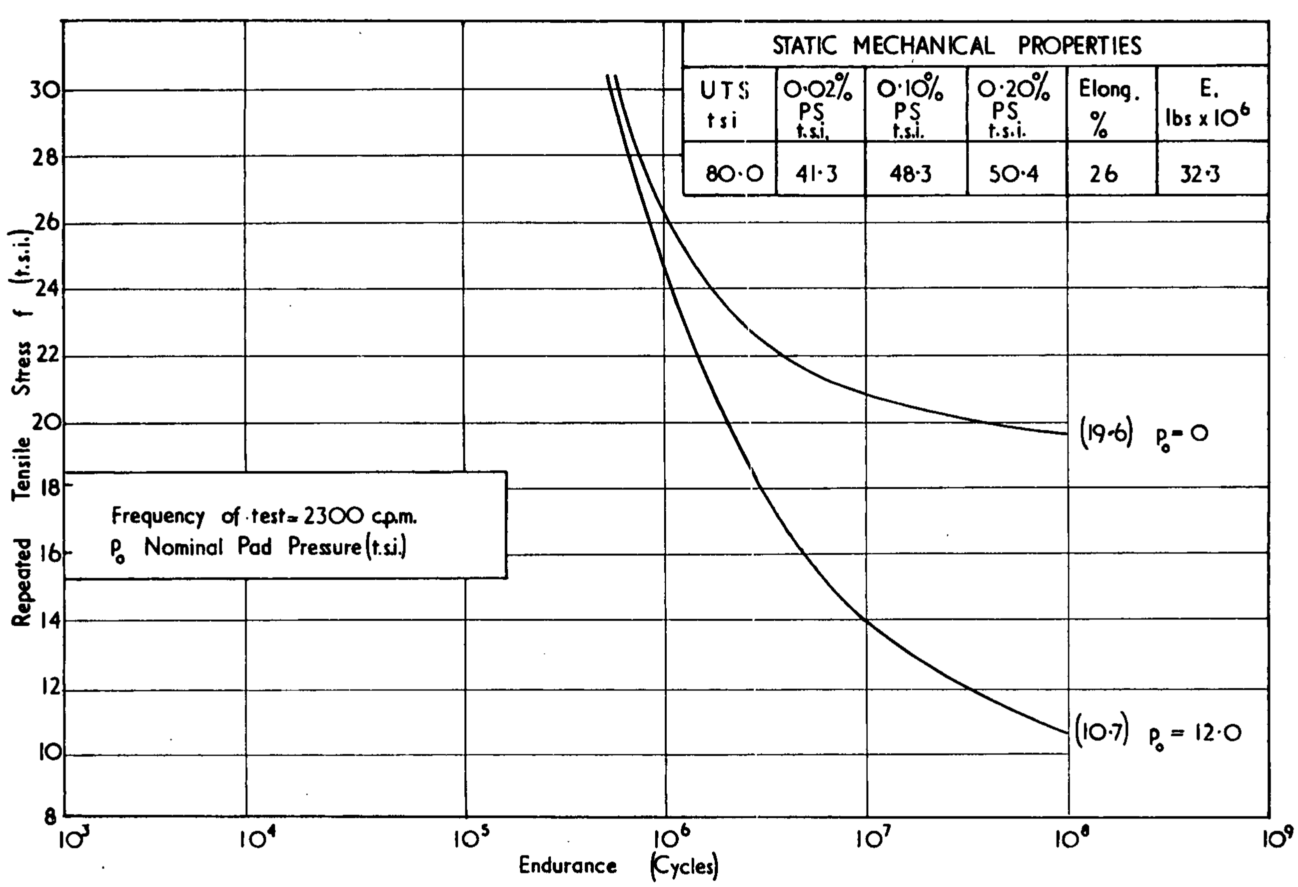

Fig.2 Fretting fatigue. Nimonic 90 alloy, solution treated 1080°C, precipitated 700°C

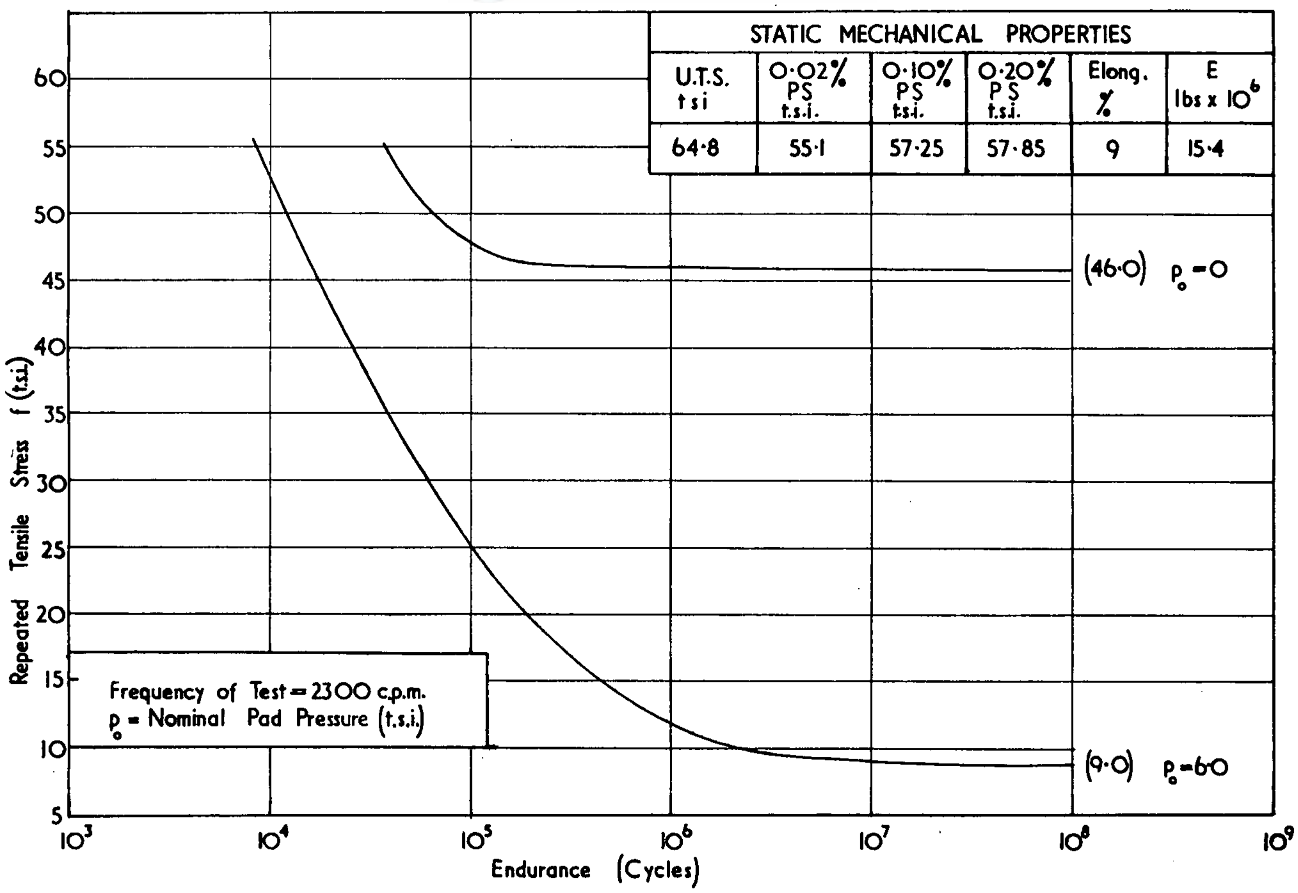

Fig.3 Fretting fatigue. Titanium alloy (6% Al 4% V), annealed 700°C

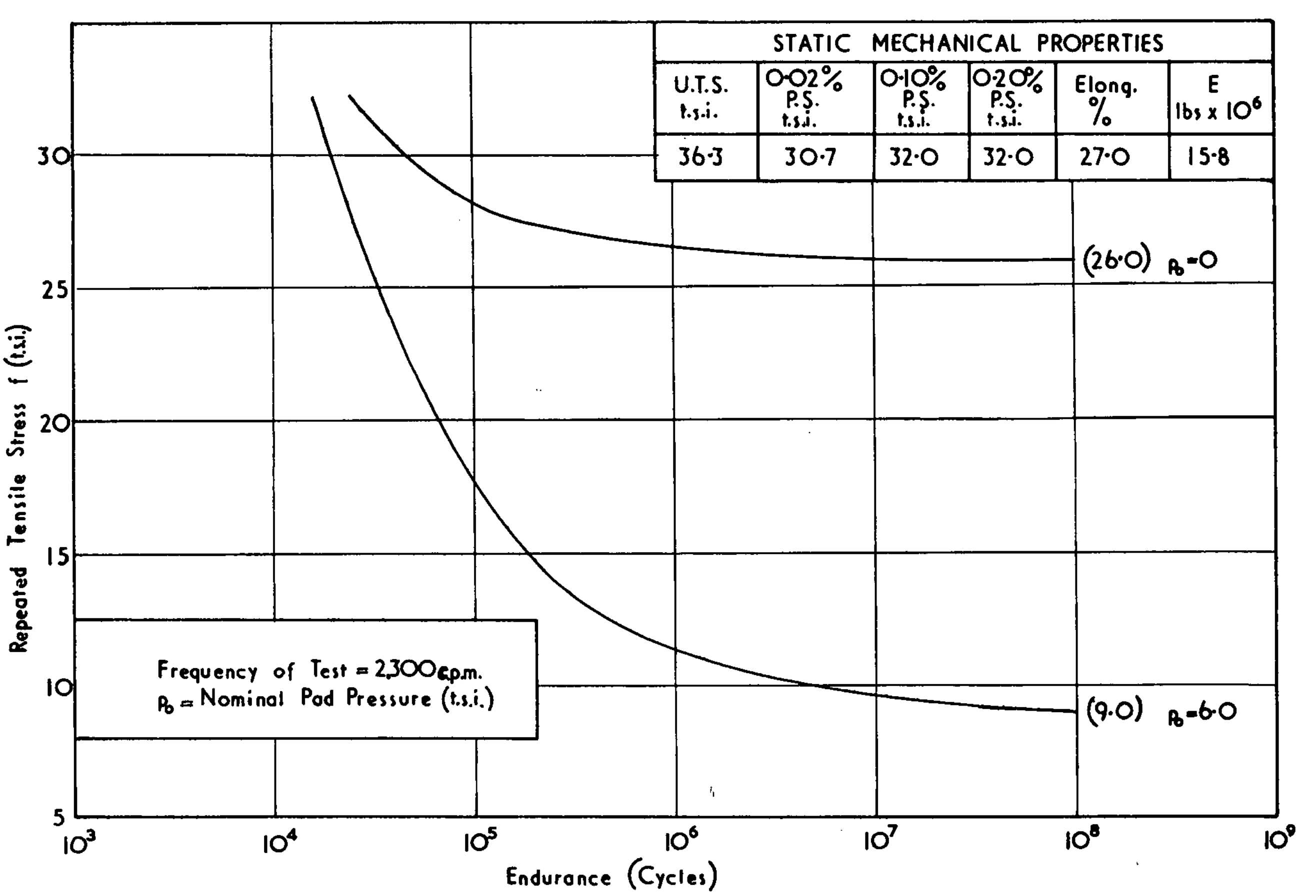

Fig.4 Fretting fâtigue. Titanium alloy (2.6% Cu), annealed 790°C

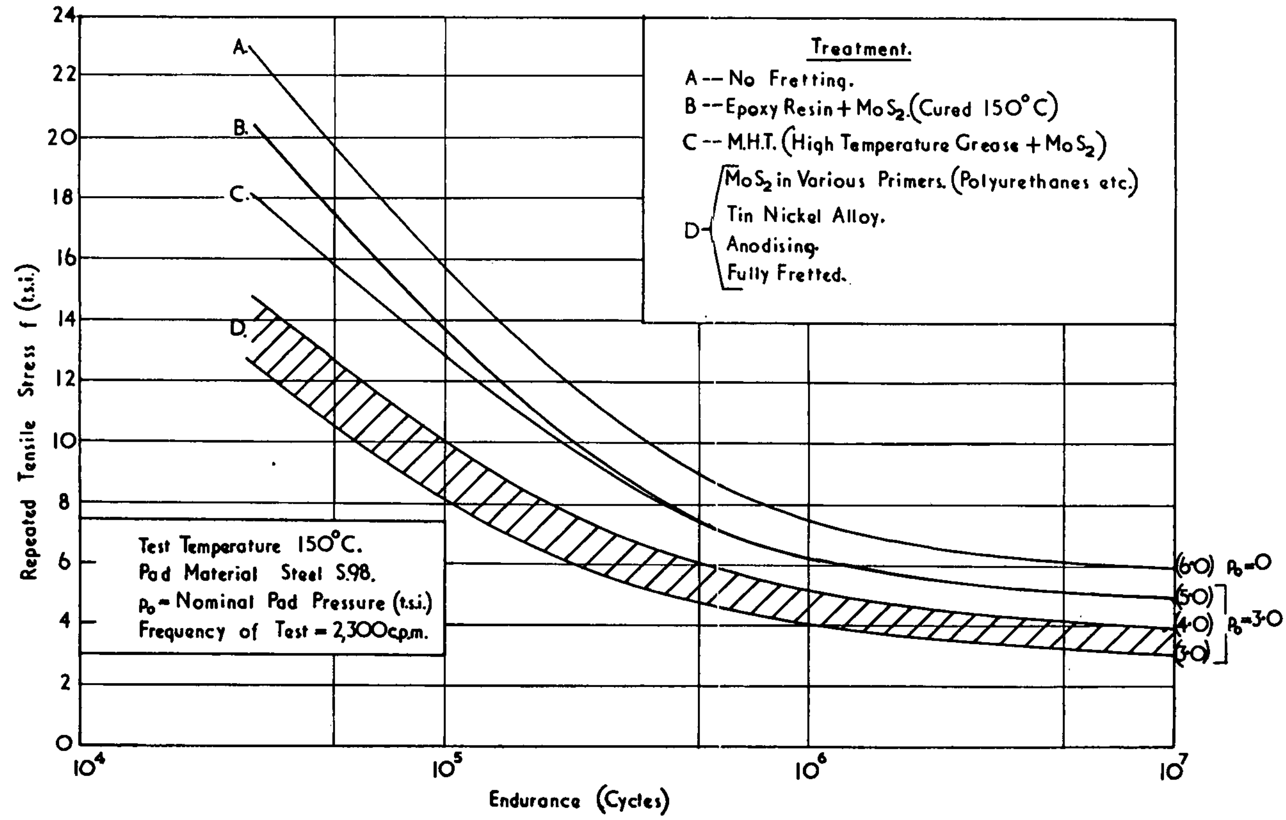

Fig.5 Fretting fatigue. Aluminium alloy DTD 5070A (2.5% Cu 1.5% Mg 1.2% Ni)

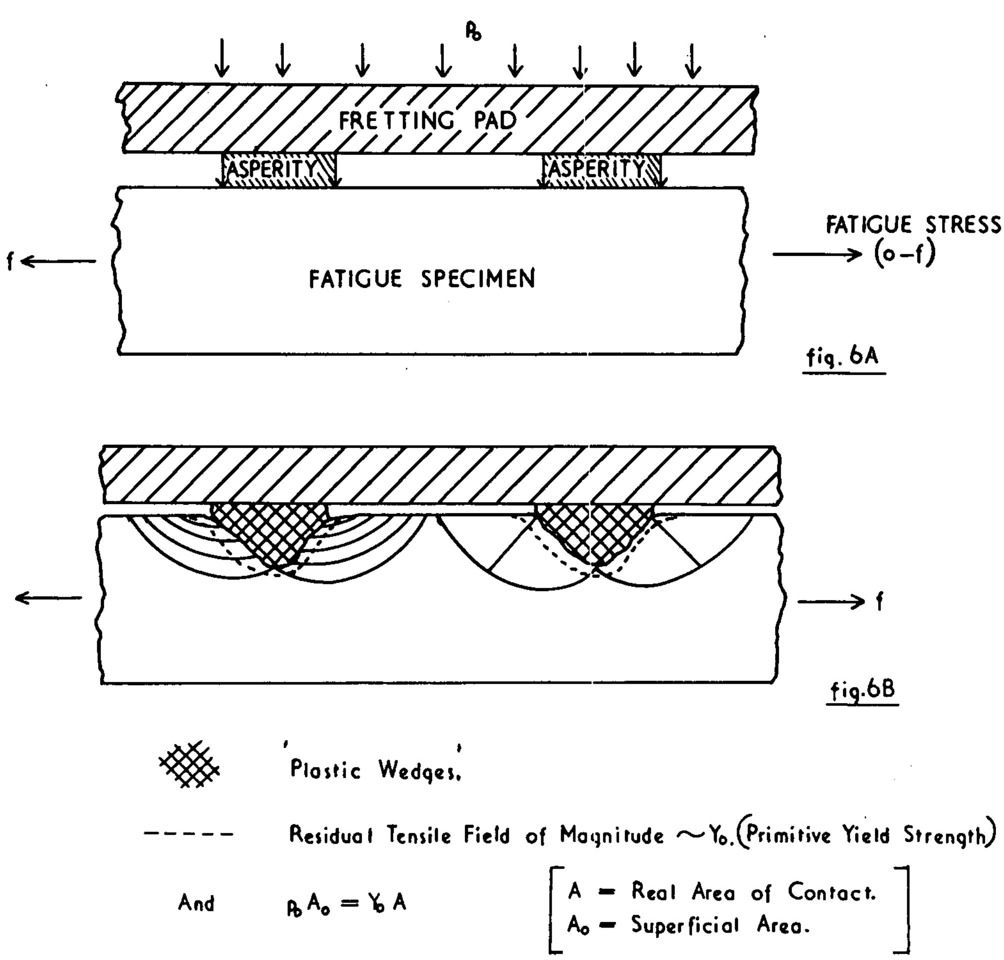

Fig.6 Residual stress fields

Fig.7 Optical photomicrograph of subsidiary fatigue crack under scar.
(Taper section 1:10, magnification x 200)

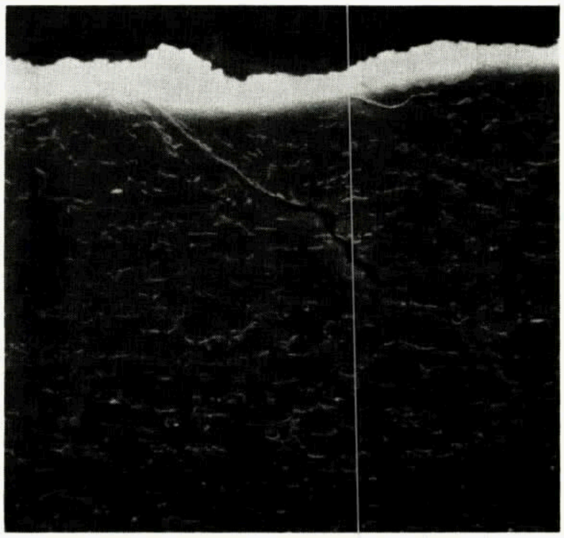

Fig.8 Scanning electron micrograph (magnification × 1300). 45^{o} fatigue crack delineating plastic zone under scar. On IMI 318A

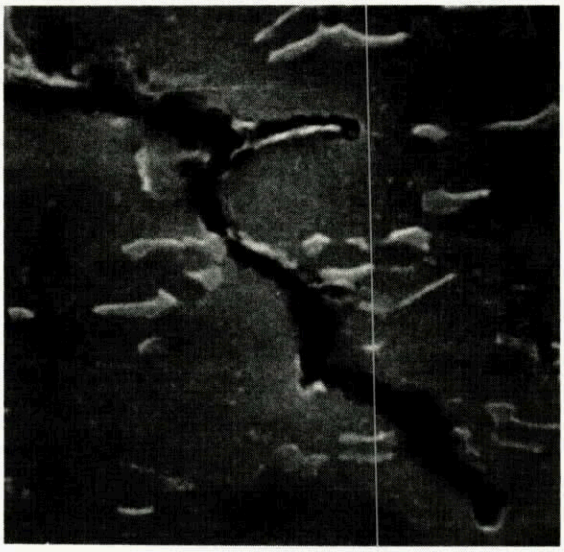

Fig.9 Scanning electron micrograph (magnification × 6500) of tip of crack shown in Figure 8. Note the crack being constrained to '$-\beta$' boundary

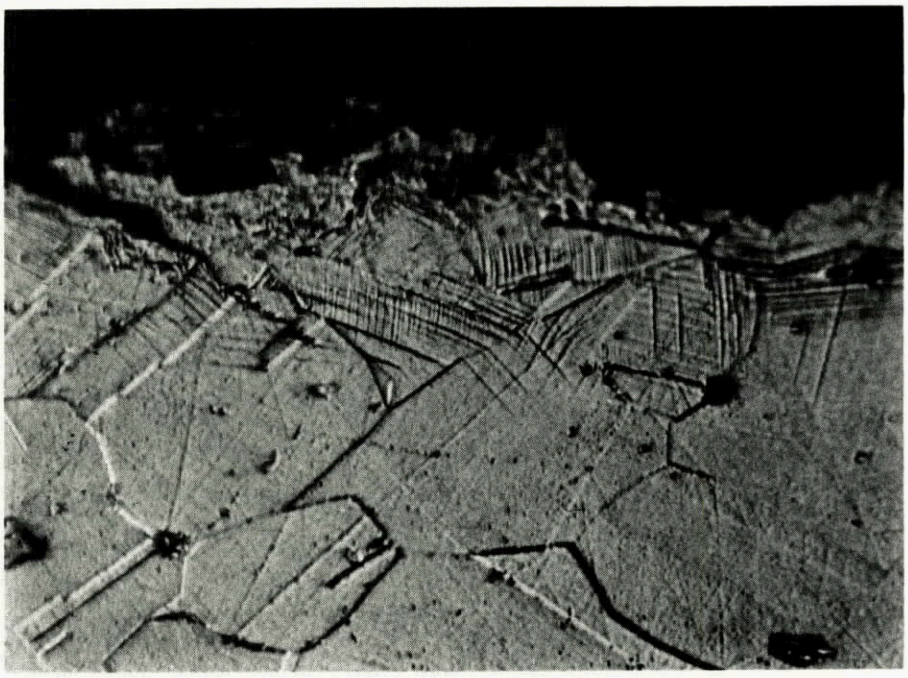

Fig.10 Optical photomicrograph under oblique lighting (magnification × 1000). Illustration of plastic wedge and slip under 'asperity-scar' with 45^{o} fatigue crack in Nimonic 90

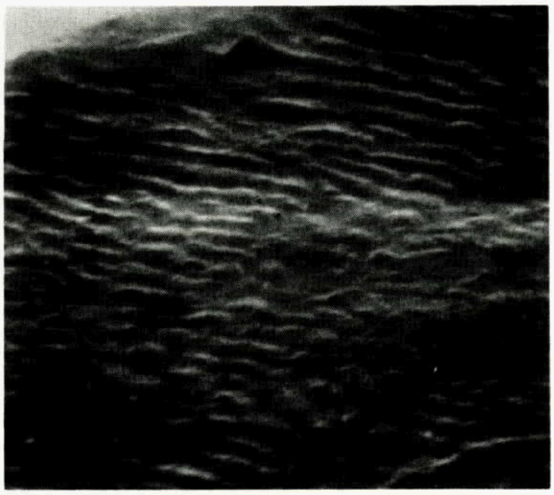

Fig.11 Scanning electron micrograph photo of striations (magnification × 2800)

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