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CUMULATIVE FRETTING FATIGUE
AS A FUNCTION OF
SLIP AMPLITUDE AND NORMAL LOAD

by

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Fretting is a form of surface damage which occurs when two surfaces in contact experience cyclic displacement, of the order of one-thousandth of an inch, with respect to each other. This damage typically culminates in the failure of a load-carrying member or in the jamming of a mechanism through reduction of operating clearances by fretting debris.

Fretting can occur in situations where the contact surfaces are designed to be stationary and also when they are meant to undergo relative motion with respect to each other. For example, the inner race of a frictionless bearing is press-fitted to an axle. As the axle flexes under load, cyclic strains result in fretting at the interface of the press-fit and the fatigue life of the axle is reduced. Alternatively, the same bearing may experience vibration while nominally at rest. The amplitude of oscillation may be too small for normal lubrication to be effective, and fretting can occur between the balls and race.

The consequences of fretting damage can range from minor inconvenience to loss of human life. Reduction in fatigue strength is a particularly dangerous manifestation.

1.2 The General Fretting Problem

Fretting is considered to be basically a physical wear process. However, the presence of an oxygen atmosphere in most situations introduces a chemical component. The inseparability of these phenomena is reflected by synonymous use of the terms "fretting" and "fretting corrosion".

While there is no one exclusively acceptable explanation of the fretting mechanism, it is possible to envisage a model which demonstrates the general elements of prevailing theories. The physical process is regarded as fundamental to surface deterioration and the generation of wear particles. The chemical process is viewed as a controlling influence on the ability of the physical process to operate. (In reality, the physical process undoubtedly influences the potential for chemical action as well.)

The physical process centres around the deformation and adhesion of surface asperities, or local high spots. As the parent materials are pressed together and subsequently experience cyclic displacement with respect to each other, these asperities are subjected to large cyclic stresses and strains derived from the normal interface pressure and the repeated application of shear forces. Then as a result of tearing, scraping and fatiguing, metal transfer occurs and loose wear particles are produced. The cyclic, small-amplitude fretting motion dictates entrapment of these particles and the development of a separating layer between the surfaces. The damage process now becomes a mild one of abrasion or scouring.

The chemical element appears in the form of the oxide layer which is present on most engineering materials before fretting starts. Its initial resistance to break-up and removal, and its ability to replenish itself during the fretting process both significantly affect the adhesion phase. The physical properties of the dislodged oxide layer and the virgin wear particles which subsequently oxidize influence the abrasion phase.

A statement of the effect of a fretting variable has meaning only in the context of the method which has been used to assess the severity of damage. Visual appearance, depth, and volume of the wear scar, and specimen weight loss are examples of indices which have been used in the study of fretting as a wear process. The following general trends[1] are found in fretting literature surveys (1-11):

(a) The occurrence of slip between the contacting surfaces is a necessary condition. Damage increases with increasing slip until the large amplitude of motion facilitates the escape of debris and the problem becomes one of ordinary wear.

(b) Damage increases with increasing normal pressure, if the slip amplitude is maintained. There is no nominal pressure below which damage will not occur.

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1 These statements are applicable to severity of wear but not, in general, to severity of fatigue damage. The fretting fatigue relationshp is surveyed in Chapter Two.

(c) Damage increases with the number of fretting cycles. The rate of damage is initially high but falls to a low constant rate. A frequency effect is occasionally observed.

(d) Damage is greater at low temperatures, in an atmosphere containing oxygen, at low relative humidity in the presence of oxides, and between like materials and hard materials.

(e) Some chemical surface treatments and solid lubricants will prevent fretting, but liquid lubricants can only postpone damage.

1.3 The Scope of This Investigation

This investigation is concerned with the reduction of fatigue life by fretting. Conditions of simultaneous fretting-fatiguing are established in terms of the magnitudes of slip and normal force at the fretting interface. These conditions are combined in various ways to study the development of cumulative fatigue damage under conditions of fretting.

CHAPTER 2

REVIEW OF FRETTING FATIGUE LITERATURE

2.1 Philosophy of Experimental Approach

Fretting fatigue appears frequently as a serious engineering problem under actual service conditions, and many investigators have attempted to understand the mechanisms at work through experimentation in the laboratory. Historically, fretting was first reported in 1911 by Eden, Rose and Cummingham (12) who noticed it in the grips of their fatigue testing machine. Tomlinson (13) initiated the study of fretting in the laboratory in 1927, but fretting fatigue was not accorded the same distinction until Warlow-Davies' (14) delineation in 1941 of the experimental difficulties.

A full appreciation of the findings of fretting fatigue researches requires an awareness of the variety of definitions and evaluative techniques, and the broad philosophical dilemma which has encouraged their proliferation.

Three methods of approach that have been used in the study of fretting and fretting fatigue are mechanical, chemical and metallurgical. A mechanical approach might use reduction in fatigue life as a measure of fretting damage. A chemical approach might determine the composition of the debris, while a metallurgical approach might examine a section through the wear scar to observe the characteristics of fatigue cracks in the region.

While these methods and many others are used singly and in combination, fretting as a general wear problem and fretting fatigue as an apparent particular manifestation of the former, each require very different experimental indicators. Some indices of the severity of fretting were introduced in Chapter One. The index of fretting fatigue damage has usually been the number of cycles to failure.

The accumulation of data based on these different indices permits a very fundamental question to be assessed. Does a fatigue mechanism cause fretting wear, or does the fretting action result in fatigue damage? Harris (15) interprets many investigators' theories as indicating fatigue as the causative agent.

> 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 wake of the sliding contact . . . .

Pavliscak (16) finds implicit support in prevalent terminology for fretting as the causative agent.

> Fretting manifests itself by producing one of three associated phenomena, viz., (1) fretting corrosion, (2) fretting wear, or (3) fretting-fatigue. These compound names identify fretting as the causative agent; and corrosion, wear, or fatigue damage are observed results. . . .

Milestone (17) reinforced this view in 1966 when he summarized:

> While separate explanations for the mechanism of fretting-fatigue have not been specifically spelled out, it is usually implied that the fatigue damage is caused by the general deterioration of the surface . . . .

Some support has grown for a model incorporating simultaneous mechanisms rather than a specific cause-effect relationship. Waterhouse (3) did not believe it correct to say that fretting corrosion causes fatigue but that ". . . conditions which favour fretting are often those which favour fatigue. . . ." In particular, Walker (5) considered that ". . . the fatigue lives appropriate to fretting-induced cracks and those appropriate to 'natural' cracks have each their own statistical pattern, and these patterns overlap. . . ." Stepanov (18) studied S-N curves representative of fretting and non-fretting conditions and concluded that at stresses above the knee, ". . . disintegration of the metal is determined by the parallel development of purely fatigue processes and processes associated with fretting corrosion. . . ." Below the knee, the latter process alone acts with an intensity which is independent of the cyclic loading amplitude. Similarly, Oding and Ivanova (19) envisage two distinct processes of vacancy formation under conditions of fretting. The effectiveness of each process is dependent upon the prevalent level of fatigue stress.

These comments illustrate the diversity of opinion which surrounds the question of causation. This question may not be essential in the application of experimental results to the solution of engineering problems in service, but it is unavoidable when proposing a model to explain those results.

Geometric stress concentration is a further unknown factor in the fretting fatigue model. While its complicity is generally accepted, the magnitude of any allowance to be made on its behalf remains basically indeterminate. Forrest (20, p. 230) sees stress concentration as a detractor from fretting's image as the sole causative agent.

> . . . The whole of the reductions in fatigue strength need not be attributed entirely to fretting corrosion, because the fatigue strength must also be influenced by the stress concentrations at the changes in section of the clamped assemblies, and by the clamping pressures, but there is no doubt that the fretting contributes considerably to the result.

Warlow-Davies (14) takes a harsher view and considers the presence of stress concentration to completely obliterate sound attribution to fretting.

> . . . fatigue flaws in machine parts are often found to have started from surfaces previously damaged by fretting. This gives no direct evidence of the effect of fretting corrosion on fatigue strength, however, for the reason that these regions suffer unknown concentrations of stress. . . .

Wright and O'Connor (21) emphasize the inter-relationship between stress concentration and fretting--one which may render them inseparable not only in measurement but also in abstraction.

> . . . The severity of fretting damage . . . depends on the amplitude of slip between the surfaces . . . . However, the amplitude of slip depends on the distribution of normal and shear stresses on the interface . . ., i.e., on the geometric stress concentration. . . .

In summary the experimenter, armed with a variety of possible techniques, must make a selection among them without the assistance of an established model for the process he is about to study. In addition, while geometric stress concentraction may be a physical necessity to the conditions which give rise to fretting, it may behave in an experiment as a significant variable which can be neither assessed nor controlled.

2.2 Methods of Experimental Approach

The experimental methods which have been used in the study of fretting fatigue, while differing greatly in the particular, can be generally identified as belonging to one of two basic types. In the first, fretting and fatiguing occur simultaneously until failure occurs. In the second, the fatigue evaluation is performed subsequently to and separately from the initial fretting operation. These methods are referred to as one- and two-step tests respectively.

The one-step method has been used because of its closer resemblance to service conditions and in deference to a concern that the conjoint action of fretting-fatiguing might be more detrimental than their separate actions.

The two-step test preceded its counterpart, and was first used by Warlow-Davies (14) who has been one of the few investigators to explain his reasons for choosing it.

> . . . The difficulty of separating the effect of the fretting corrosion from that of the stress concentrations inherent in the conditions which produce it, convinced the author that it would be more profitable to attempt to separate the fatigue test from the fretting action altogether. . . . By this means the damaging effect of the fretting corrosion of the surface could be measured by the percentage loss in fatigue strength as compared with unfretted specimens. Such tests are analagous to the determinations of percentage damage due to stressless chemical corrosion . . . .

The concern over conjoint action, which Warlow-Davies (14) shared, led to an early modification of the two-step test. The nominally static stress condition during the initial fretting was replaced by fatiguing stress. In addition, this change was inherent in a new technique which utilized the elongation and contraction of a length of specimen experiencing fatiguing strains to produce the relative sliding at the specimen-fretting pad interface.

The test arrangement most appropriate for studying the fretting phenomenon may not necessarily be the arrangement most closely resembling the particular service conditions under which the serious consequences of fretting are dramatically illustrated. Milestone (17) acknowledged the usual peristence of fretting throughout the service life of a part, but chose a two-step test because he considered, in an experimental programme ". . . that the conditions of fretting, including the number of cycles, should be held constant in order to permit comparison of results."

The effect of an independent variable which has been observed with one fretting arrangement may not be validly comparable to effects observed under different procedures. This point is illustrated by Fenner and Field (22).

> The effect of mean stress under these conditions [two-stage tests] is quite different from that obtained when the clamps are left on for the total duration of the test [one-step test], thereby permitting development of the maximum fretting-fatigue damage obtainable under the conditions of each particular test. . . .

In further work, Field (23) employed both one- and two-step tests in studying the effect of the direction of fretting in relation to the fatigue stress. Both methods showed fretting in a parallel direction to be more damaging than in the transverse direction. However, the severity of damage was greater for the one-step test.

Methods of testing used by fretting investigators employing fatigue stresses in their tests, have been classified in Appendix A to facilitate an appreciation of their findings.

2.3 The Initiation of Fatigue Cracks under Fretting Conditions

Any experimental study dealing with crack initiation must define when a crack is considered to exist. Grosskreutz (24, pp. 14, 16) considers that "from the standpoint of fatigue mechanisms, the accepted practice is to define a crack in terms of the highest resolving power instrument available--presently the electron microscope." In some writings (25, p. 38) the distinction is made between microcracks and macrocracks: "Microcracks are cracks that are one or two grain diameters in length. Macrocracks (usually just called cracks) are defects that are larger than this." In the fretting fatigue literature such definitions are usually implicit by default. However, Nishioka and Hirakawa (26) considered fatigue cracks to be present when they could be detected with an optical microscope at 400x. Many investigators have observed fatigue cracks which have initiated under fretting conditions, and their findings, on whatever level of resolution, are presented in the paragraphs to follow.

An important aspect of crack initiation is the evidence to support the existence of local stress fields induced by the fretting configuration. This situation has been examined on several levels, one of which is a stress analysis based on a cylinder in contact with a plane surface. Values for the necessary parameters are obtained experimentally, and the results compared with multi-axial failure theories. Milestone (17) used this approach and his research suggested that

> . . . fretting and fretting-fatigue are caused because high-amplitude, cyclic stresses are induced into the material adjoining the contacting surfaces. These stresses are the result of a combination of (1) locally high normal pressures between the contacting surfaces, (2) high values of coefficient-of-friction that develop at the interface, and (3) the cyclic nature of the relative sliding motion. If the conditions are sufficiently critical, fatigue cracks could be initiated. . . .

In contrast to this macroscopic scale of analysis, Harris (15) has extended results of photoelastic stress studies of compression pads to plastically-compressed asperities at the fretting interface. His findings establish the existence of compensating residual tensile stress fields which are of sufficient magnitude to make highly probable the nucleation of cracks when fatigue stresses are superimposed.

In a similar fashion Johnson and O'Connor (27) placed particular importance on concentrations of shear stress which develop near the edge of a fretting pad. Wright and O'Connor (21) concluded that such regions of discontinuous contact undergoing oscillating slip could explain strength reductions due to fretting, but only if a bulk propagating stress was simultaneously present to render the volume of affected material sufficient for the initiation of fatigue cracks. Work done by Field (23) suggests that the alternating frictional shear stress is more influential than the propagating fatigue stress. Tests were conducted with the fretting movement either parallel or transverse to the direction of the fatigue stress. While a crack proved more detrimental to the life of the fatigue specimen if it ran transverse to the direction of the bulk fatigue stress, in both cases the planes of the fretting-induced cracks were perpendicular to the direction of fretting.

This fundamental role effected by frictional shear stress receives indirect support from the findings of Bethune and Waterhouse (28) that ". . . when the adhesion [developed between fretted surfaces] exceeds a certain critical value the fatigue life of the steel is low. . . ." Nishioka and Hirakawa (29) considered the frictional fretting force to be but one of the causes of reduced fatigue strength, whereas Liu, Corten, and Sinclair (30) suggested that the repeated frictional shear stress on the asperities constitutes the primary mechanism responsible for fretting fatigue damage.

Surface irregularities produced by fretting are not generally considered capable of raising bulk stresses to significant levels. Nishioka and Hirakawa (29) reached this conclusion even though they observed in the fretted area small and relatively large pits having diameters 10 to 30 microns, and 0.1 to 0.4 mm, respectively. Talysurf surveys of damaged surfaces convinced Waterhouse (31) ". . . that generally the type of pit produced would not cause serious concentration of stress. . . ." Wright and O'Connor (21) pronounced such increased surface roughness innocuous on the basis of their findings that "fretting applied in the absence of a propagating [bulk] load, either static or dynamic, does not affect the subsequent fatigue strength."

Numerous investigators (22, 32, 33) have preferred to identify the initiation of cracks with observable strain conditions in the fretted region. On the basis of metallographic examinations of fretted specimens they concur that crack initiation is associated with high strain fatigue which occurs at the inter-facial micro-welds.

The locations of the initiated fatigue cracks suggest, albeit not unanimously, that fretting is the causative agent. While some investigators (16, 21, 29, 31, 33) definitely consider the initiation points as being primarily within the fretted region, Harris (15) found that ". . . nucleation seems to occur with equal probability within the fretting scar or just outside the scar boundary . . . ." On the basis of photoelastic studies, Harris (34) attributed this enigma to the existence of surface tensile stress which ". . . peaked up to some 2.0 to 2.5 times the value of the superficial contact pressure just outside the contact area . . . ." Still others (16, 29, 35) consider the critical location for crack initiation to be the boundaries between slip and non-slip regions, whether they be at the outer edge of the fretting pad or at discontinuities within the nominal fretted area.

Investigators (22, 23) have often observed that the fatigue cracks, as first initiated in the fretted region, tend to lie in planes which are inclined to the surface. Wright and O'Connor (21) consider the initial direction ". . . to be consistent . . . with an Hertzian contact stress field at limiting friction." Harris (15) interprets their initial inclination, 45^{o} to the principal fatigue stress axis, as evidence of their being ". . . strongly controlled by the residual stress fields generated along the plastic peripheries of the asperities." Waterhouse (36) found that the fretting of steel on steel resulted in numerous cracks which were always initially very obliquely angled to the surface. While cracks produced by stainless steel on steel were at 60^{o} to 70^{o} to the surface, those produced by other materials on steel were occasional and normal to the direction of fatigue stress.

In summary, the initiation of fatigue cracks by fretting action is credible in the light of stress analyses with experimental correlation, photoelastic studies, and evidence of high strain fatigue. Residual stress fields and concentrations of shear stress appear to be instrumental in initiating usually obliquely inclined fatigue cracks within or in the near vicinity of the fretting scar.

2.4 The Propagation of Fatigue Cracks Under Fretting Conditions

Evidence of the ability of fretting-induced stresses to assist the propagation of cracks is not conclusive. Some findings are concerned with fatigue cracks per se while others must be viewed in the context of a particular fretting fatigue test method.

It is not clear, in a fretting situation, whether a higher nominal fatigue stress is necessary to propagate an existing crack. Milestone (17) considered it ". . . generally agreed that a fatigue crack will propagate at a lower stress amplitude than that required to initiate it," while Horger (37) found that fretting permitted the initiation of cracks at very low stresses but that the cracks did not spread unless the stress was raised. Nishioka and Hirakawa (26) considered the presence of non-propagating fatigue cracks in regions of fretting corrosion to be evidence of the limited region-of-influence of fretting-induced stresses.

> . . . The influence of fretting on the stress state is limited to only the very thin surface layer of the specimen. . . . After a slight growth of crack from the surface, there exists no influence of fretting on the stress state, which controls the propagation of fatigue cracks.

There are conflicting statements as to whether stress or strain is the necessary ingredient for propagation. Harris (15) states in one context

> . . . 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 in another that

> . . . crack growth rates are proportional to the cube of the strain (and not stress) and non-propagating cracks, defined by zero rate, are characterized by a threshold strain, which is approximately 5×10^{-4} for repeated tensile stressing and 2.86×10^{-4} for alternating stressing.

Whether the criterion be stress or strain, a particular interpretation of the nominal fatigue stresses associated with endurance under fretting conditions has evolved. This index of damage appears to say more about the bulk propagation properties of the specimen than about the fretting process itself. Milestone (17) concluded that ". . . for the fretted specimens the fatigue results were actually a measure of the fatigue-crack-propagation stress amplitude, rather than crack initiation stress amplitude." Frost (38) expresses a similar interpretation.

> . . . 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. . . .

And finally, Field and Waters (32) observed that

> . . . the minimum fretting-fatigue strengths at the various mean stresses nearly all corresponded to a limiting range of cyclic tensile stress of 7 - 8½ tons/ in^2; this conforms approximately to the simple hypothesis that this is the critical parameter for the propagation of the cracks produced by fretting. . . .

A change in inclination of propagating cracks is observed which correlates with the degree of plastic deformation of the surrounding material. Harris (34) found that ". . . fatigue nucleation in the contact surface often propagates as short inclined cracks but then deviates to propagate at right angles to the principal fatigue stress direction. . . ." Waterhouse (31) observed similar inclinations and, in addition, noted that the transition occurred during passage from the severely plastically deformed fretted region to the more remote unaffected material. Fenner and Field (22) conducted tests in vacuo and in air and observed the mode of propagation to be influenced by the presence of air.

> ... once they had left the fretting marks, the cracks propagated obliquely to the specimen axis, in most cases at an angle of about 45 degrees, instead of 90 degrees to it as in air. This shear mode of failure indicates a mechanism of crack propagation in vacuo different from that in air; it is presumed that this is not connected with the fretting process since the general direction of the cracks within the fretting marks was, as in air, at right angles to the direction of fretting movement, though small 45 degree steps could be observed on close examination.

Some investigators (17, 22, 31) consider the coalescence of propagating fatigue cracks to be one of the mechanisms involved in the generation of loose wear particles.

In summary, opinions differ on the magnitude of stress necessary for propagation relative to that for initiation, and on the predominance of stress or strain as the determinant of rate of propagation. There is agreement that endurance in fretting fatigue tests is primarily representative of bulk propagation properties. There is evidence that the fretting induced stresses have a limited region of influence, and that plastic deformation of the material and the presence of air influence the inclination of propagating cracks.

2.5 The Effects of Fretting Variables on Overall Fatigue Performance

2.5.1 Fretting Damage Versus Fatigue Damage

While the question of whether fretting can be considered to cause reduction in fatigue life has drawn no conclusive evidence from the literature, investigators have commented on the severity of fretting wear in relation to the severity of fatigue damage.

In some studies the effect of fretting wear has been minimal. Fenner and Field (22) found that ". . . The abrasive phase, while setting in at an early stage and being mainly responsible for the wear produced after large numbers of cycles, has little effect on fatigue strength. . . ." Field and Waters (32) similarly stated, ". . . Excessive fretting wear, which does not cause much fatigue damage, has been shown to result in shallow surface depressions not associated with surface cracks." Pavliscak (16) observed a positive correlation between fatigue strength and fretting wear: ". . . Joints that exhibited the greatest wear damage also had the highest fretting-fatigue strength. . . ." In particular, "joints with perhaps two orders-of-magnitude more fretting-wear, exhibited more than one third greater fretting-fatigue strength." Field and Waters (32) attributed such immunity to the prevention of microweld formation by a separating layer of trapped debris, and to the abrading of crack nuclei prior to their propagation.

However, a word of caution is necessary because Waterhouse (36) reported that ". . . although the visible damage may be slight the fatigue damage may be serious." This inability of fretting wear to reveal the extent of fatigue damage, conservatively or otherwise, has been expressed by Comyn and Furlani (7).

> Although the correlation between fretting corrosion and fatigue is acknowledged, investigators have noted . . . that the onset of fatigue does not appear to have any relation to the extent or severity of fretting. . . .

It is perhaps because of this indifference to wear that some investigators began using the number of fretting cycles as an independent variable in their experiments. This approach has been incorporated primarily in two-stage testing and it involves the development of what is termed "significant damage". Fenner and Field (22) defined it specifically:

> . . . the stage at which significant damage had been caused was judged by determining whether or not a crack could be propagated through the specimen, from one or more of the fretted areas, by applying a stress in the [second] unclamped stage of 12.5 ± 5.5 tons/sq. in.; . . . it was expected that at this stress even very small initial cracks would propagate in relatively few cycles. . . .

The number of fretting cycles has assumed importance in various contexts. Horger (37) stated, "The allowable stress, to prevent cracks initiating, appears to be a function of time or number of stress cycles, " and Wright and O'Connor (21) expressed the view that "the full strength-reduction due to fretting is not achieved until several hundreds of thousands of cycles of reversed slip have occurred. . . ." Several investigators (22, 39, 40) have found that fretting fatigue damage is fully developed after one-fifth of the resultant life of the part, that is (40), ". . . when fretting is allowed to persist for more than one-fifth of the life, the endurance is about the same as if fretting were allowed to continue to the point of fracture . . . ." The effect of removing the fretting prior to the critical fifth is not clear. Such removal was considered by Wright (39) to be a dependable remedy, and by Philips and Low (40) to result in a negligible fretting effect on fatigue life. However, Fenner and Field (22) state that this early removal of fretting does not preclude the development of "significant damage". Waterhouse (31) plotted cycles-to-failure versus cycles-of-fretting (Figure 1), and determined a fretting fatigue limit--the maximum number of initial fretting fatigue cycles which did not seriously reduce the life of the specimen in a particular, subsequent fatigue test.

2.5.2 Debris Entrapment

The effect of entrapment of the fretting debris on endurance depends upon the application. Entrapment is beneficial if the interface pressure remains constant as wear proceeds, as when the pressure is the result of gravitational forces. Milestone (17) considers that the separating layer of debris prevents reinstatement of the damaging stress fields associated with large values of coefficient of friction. Entrapment is detrimental when it results in increased interface pressure, as in a press-fit. Starkey, Marco and Collins (41) envision the

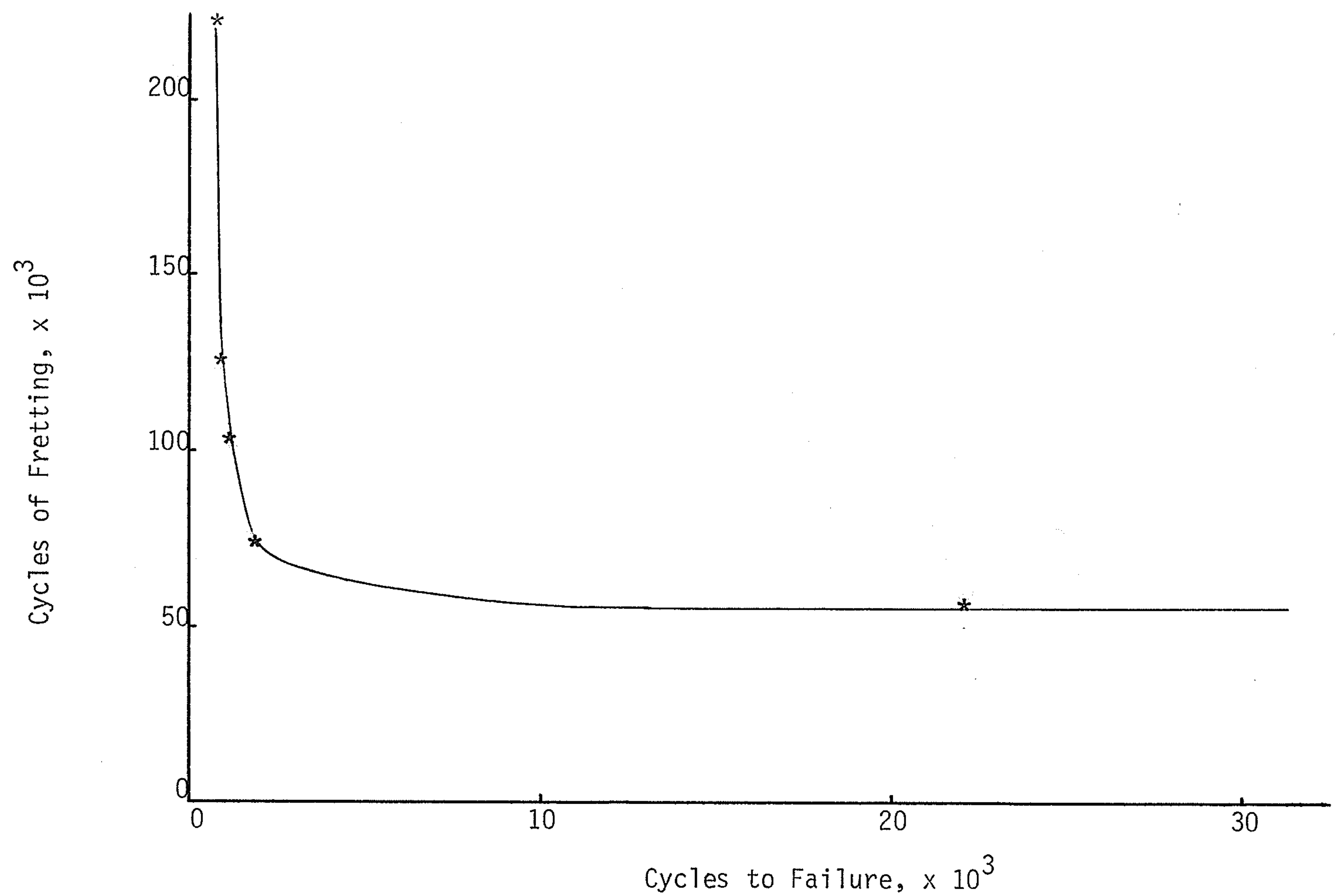


Figure 1. Number of Fretting Cycles Versus Number of Cycles to Failure (31)

development of pressure increases on a very local scale due to the substantially greater specific volume of most oxides compared to their parent materials.

Pavliscak (16) reported a significantly increased fretting fatigue strength for metallic joints when a means was provided for the escape of debris; as for example, ". . . interface clearance or any sacrificial coating that behaves similar to a clearance."

2.5.3 Slip

Slip, as it occurs at the fretting interface, has particular characteristics. Harris (34) describes engineering applications in which slip is dependent on numerous other variables.

> . . . in design elements utilizing press and push-fit pins, shrink-fit shafts, bolted and riveted joints, relative slip amplitudes can be generated with magnitudes dependent on the fatigue strain amplitudes and the conditions at the contact surfaces, such as normal pressures and frictional forces.

The assumption that a nominal constant slip occurs over the entire fretting interface becomes less justified as the contact area increases. Wright and O'Connor (21) considered that the amplitude of slip in their joint assemblies ". . . varied from zero at the inner boundaries between the slip-no slip regions to a maximum at the edges of the interfaces. . . ." Johnson and O'Connor (27) showed that ". . . in the majority of fretting situations oscillating micro-slip at the edge of the contact is inevitable under the action of the smallest oscillating forces. . . ." They considered this micro-slip in the built-up assembly to occur wherever concentrations of shear stress would develop in a geometrically similar solid piece.

The concept of a slip-no slip boundary is the focal point of a continuing damage process described by Waterhouse and Taylor (35).

> . . . if the surfaces are curved or cylindrical, there exists, below a critical value of the shear, a central area where the frictional force is greater than the shear traction, and slip does not occur over this area. . . . At the boundary between the slip and non-slip areas there is a high stress concentration . . . . This is the point of initiation of the fatigue crack . . . . When the crack is formed and has grown a little, it relieves the concentration at this point. The wearing away of the surface in the adjacent slip region also assists in the stress reduction. The situation is now as though the dimensions . . . [of the original overall contact area] were reduced to the original non-slip area. The normal pressure is increased and the process starts again with the slip occurring over the edges of this area. The stress concentration moves to the new boundary between the slip and non-slip areas and is greater than before, and therefore the crack grows more rapidly than the first crack. . . .

If slip can be made to occur over the entire interface, by increasing the slip amplitude or decreasing the coefficient of friction, then fatigue damage will be reduced (35). By contrast, Wright and O'Connor (21) place importance on the resultant percentage of the interface experiencing slip, rather than the slip-no slip boundary itself.

> . . . In general, if the slip region is large the geometric stress concentration is low and fretting is the dominant factor. If the slip region is small the fatigue strength is determined principally by the overall geometric stress concentration.

In general, investigators have preferred to quote nominal slip values which represent either constant slip over the interface or the maximum slip at the edge of the interface. These values are determined on the basis of calculations of nominal strain or by measurement of displacement, depending usually on the principle of operation of the fretting apparatus. The following statements of the effects of slip are made in the context of such nominal values.

Fenner and Field (22) report,

> . . . The strength reduction factor increased with increase of nominal slip [range] up to about 3×10^{-4} in.; further increase in slip brought about no additional reduction in fatigue strength.

Field and Waters (32) identify four categories of slip range in their results.

(1) slips of 2×10^{-4} inch and below generally gave only low reductions in fatigue strength, though the damage appeared to increase with increasing contact pressure;

(2) slips of $2.5 - 3 \times 10^{-4}$ inch gave moderate reductions, which were largely independent of mean stress;

(3) slips of over 3×10^{-4} inch up to 5.5×10^{-4} inch gave maximum reductions; and

(4) slips greater than the latter values, and certainly those of 10^{-3} inch and above, gave reductions no higher than those for category (2).

And finally, Cox and Fenner (42) summarized their observed effects of slip amplitude and formulated rules for design.

i) Fretting fatigue damage can be produced by slip amplitudes ranging from very low values of the order of $\pm 10^{-6}$ in. to the much higher values of $\pm 10^{-3}$ in.

ii) In the median ranges of slip amplitudes, 5×10^{-5} in. to 5×10^{-4} in., fretting has a more insidious effect since, although the damage may appear to be only superficial, small cracks may have formed which may propagate to produce failure.

iii) The experimental results . . . indicate that the reduction of fatigue strength was almost linear with the slip amplitude up to about 5×10^{-4} in.

iv) As regards strength reduction factors (K_f) and slip amplitudes, the authors suggest that the safe working rules in design would be

for $S < 10^{-4}$ in., use $K \simeq 4.0$
for $S > 2 \times 10^{-4}$ in., use $K \simeq 10.0$

While the foregoing investigators have been concerned with slip in terms of actual failure of the test specimen, Nishioka and Hirakawa (43) studied slip as it influenced the alternating stress necessary to initiate fatigue cracks. They (44) found the fatigue crack behaviour to be markedly influenced by the slip amplitude.

> For instance, even though the alternating bending stress is kept constant at 20 Kg/mm^2, different behaviours of fatigue cracks with the increase of relative slip are observed as follows. [All tests were run to 10^7 cycles] Until relative slip amplitude comes up to 5 microns [1 micron $\simeq 4 \times 10^{-5}$ inches], no fatigue crack can be observed, and between 5 and 20 microns micro-cracks which do not propagate to a fracture are observed. When the slip becomes more than 20 microns but less than about 50 microns, the crack grows to a fracture, and for a slip more than 50 microns the specimen is not broken because of severe wearing-out.

2.5.4 Normal Pressure

Investigations into the effect of normal pressure on fatigue strength have generally shown, as summarized by Milestone (17), that fatigue damage increases with normal load until a critical load is reached. ". . . Above this critical load the amount of damage is nearly independent of load and remains nearly constant. . . ." Figure 2, from a report by Liu, Corten and Sinclair (30), shows this effect.

Bowers, Finch and Goreham (45) considered the absence of a normal load effect in their tests to be expected ". . . since the actual contact pressure at asperities on the surface is likely to

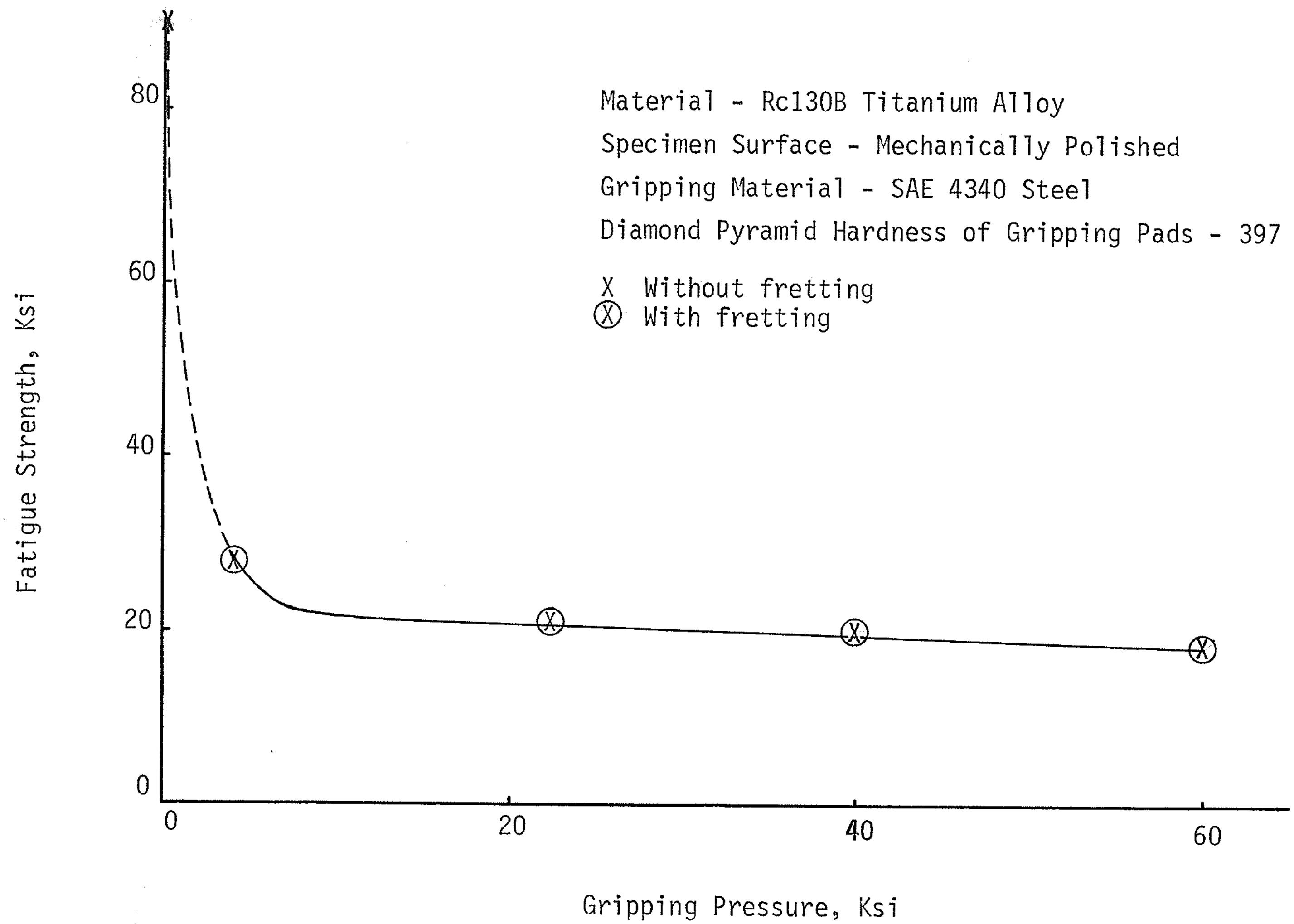


Figure 2. Influence of Gripping Pressure on Fretting Fatigue Strength (30)

approach the yield stress for the alloy irrespective of the nominal contact pressure. . . ." Liu, Corten and Sinclair (30) analyzed such contact conditions and, by relating normal pressure to hardness and the coefficient of friction, were able to derive an expression for fretting fatigue strength which was independent of the normal load.

Comyn and Furlani (7) report that ". . . Most of the experimental work has been carried out at constant load, but two reports . . . state that varying the load, during a test, aggravates fretting." While this is said primarily in relation to fretting wear, it does pose an important question for fretting fatigue.

2.5.5. Mean Stress

Mean stress has been viewed both as intrinsic to the fretting process and as an independent experimental variable. Harris (34) considers the tensile mean stress accompanying compression of the asperities to be an explanation for observed fatigue strength reductions.

> It is not unreasonable to expect, in the case of plastically compressed asperities, tensile stresses of the order of the yield strength for close-pitched asperities. . . . In the extreme case, therefore, the fatigue conditions are virtually those of a mean tensile stress ($\approx \sigma_y$) with an externally applied alternating stress. Even discounting the effect of geometric stress concentration factors dependent on surface topography, this high tensile mean stress only requires an applied alternating stress of some 5% to 7% of the tensile strength for failure.

Studies have been made of the effect of mean stress on fretting fatigue life but in many cases the results are inextricable from the test procedures. Collins and Marco (46) found that the presence of a static tensile stress during the initial fretting stage of a two-step test had little effect on the subsequent fatigue limit. However, the similar presence of a static compressive stress caused a significant strength reduction, the magnitude of which depended heavily on slip amplitude and contact pressure. They reasoned that the cracks formed in the presence of a static tensile stress developed a residual compressive stress field when the tension was released at the end of the first test stage.

Fenner and Field (22) also employed a two-stage test but used mean and alternating stresses in the initial stage. They found that the effects of mean stress depended on the level of stresses employed in the second stage. With second stage stresses of 12.5 ± 2.6 tons/sq. in. significant damage at the number of fretting cycles employed was developed under initial tensile mean stress but not under initial zero mean stress. However, with second stage stresses of 12.5 ± 5.5 tons/sq. in., significant damage formed in far fewer cycles under initial zero mean stress than under the initial tensile mean stress. In addition, they found, for a given amount of first stage damage, that the stress requirements for propagation depended on the mean stress during the second stage.

> . . . The alternating stress, required to propagate a crack from the initial fretting damage, decreases with increase in mean stress, though only slowly after reaching a mean stress of about 15 tons/sq. in. Otherwise stated, the maximum stress of the cycle, necessary for crack propagation, increases, albeit not linearly, as the alternating stress decreases.

Field and Waters (32) employed a one-step test and in spite of considerable interaction with slip, observed greater fatigue strength reductions under tensile mean stress than under zero mean stress.

> . . . for the most damaging slip conditions, the fatigue strength reduction factors increase rapidly from about 4½ at zero mean stress to 10 and over at tensile mean stresses of 10 tons/in.^{2} and above. For slips of about 10^{-3} inch and above, heavy fretting wear occurs and this tends to prevent the most severe reductions in fatigue strength being obtained for mean stresses below 20 tons/in.^{2}, but not for higher mean stresses.

They (47) further found that the comparative effects of fretting on the S_f/σ_B ratios (alternating fretting fatigue strength/tensile strength) of an En26 steel ($\sigma_B \simeq 67$ tons/in.^{2}) and an En30B steel ($\sigma_B \simeq 100$ tons/in.^{2}) were dependent on the mean tensile stress.

> . . . At zero mean stress and at a tensile mean stress of 10 tons/in.^{2} the minimum value of the ratio S_f/σ_B for the En30B was greater than that for the En26 steel, but the reverse was the case for mean tensile stresses of 25 and 40 tons/in.^{2}.

Nishioka and Hirakawa (26) also employed a one-step test and found the fatigue limit based on the initiation of fatigue cracks to be affected by the type of material, but not by mean stress. By comparison, the fatigue limit based on fracture increased with an increase of compressive mean stress and decreased with an increase of tensile mean stress.

2.5.6 Alternating Stress

Fenner and Field (22) deduced from their two-step tests that the specimen material was strengthened by the application of a low alternating stress during fretting in the presence of a tensile mean stress. Significant damage took longer to form, but once the damage had been developed, it propagated quickly at low alternating stress until beyond the region of influence of the fretting clamps.

2.5.7 Atmosphere

An appreciation of the effect of atmosphere on fretting fatigue would seem to first require knowledge of its effect on fatigue per se. Reichenbach (48, p. 607) considers there to be ". . . a growing feeling among many investigators that the action of the normal atmosphere is far more important in fatigue failures than heretofore thought . . . ." This unfathomed influence, in addition to differences in properties of specimen materials and their oxides, may possibly account for the differing observed effects of atmosphere on fretting fatigue performance.

Liu, Corten and Sinclair (30) stated that "exclusion of an oxygen (or air) atmosphere did not result in an improved fretting fatigue strength." However, Fenner and Field (22) observed that "in vacuo, fretting-fatigue cracks took longer both to form and to propagate than in air, and the mode of propagation was different. . . ."

Oding and Ivanova (19) took care to first establish that the fatigue limit of a chronium-nickel-molybdenum steel was not reduced in an atmosphere of molecular hydrogen. They then conducted further fretting fatigue tests up to 250 million cycles and observed ". . . a continuous reduction in the [fretted] fatigue strength both in air and an atmosphere of hydrogen."

Bethune and Waterhouse (33) found that the presence of an atmosphere reduced the adhesion between fretting surfaces which, unlike those experiencing uni-directional sliding, involves the continual disruption and recovery of oxide films. They also considered the possible effect of atmosphere on fatigue processes inherent in the fretting mechanism.

> . . . A further factor is the fatiguing of the welded junctions caused by the oscillatory nature of the motion. In the presence of air this becomes corrosion fatigue and the fatigue strength is lower than in a non-corrosive environment such as nitrogen. . . .

2.5.8 Temperature

While most fretting fatigue research has been conducted nominally at room temperature, it is probable that the fretting process itself generates higher local temperatures than prevail in the surroundings. Waterhouse (31) used X-ray back-reflection photographs of fretted areas and heat treated surfaces to show that the severe plastic deformation occurring at the former resulted in temperatures as high as 500°C. He considered the poor fatigue performance under such temperatures to be partly responsible for the fretting strength reduction.

2.5.9 Materials

Some combinations of materials fare better than others under fretting fatigue conditions, but the experimental results can be contradictory. Corten (49) fretted similar and dissimilar metals against a hard steel fatigue specimen and found the hardest and most similar material to be the most deleterious. Waterhouse (36) fretted various metals and alloys on a mild steel fatigue specimen, and in addition to finding similar materials not to be the worst combination, he described properties which correlated with superior fretting fatigue performance.

> . . . The materials which are least deleterious appear to be those with low hardness, high thermal conductivity, high stacking fault energy (and hence low work-hardening ability), and low recrystallization temperature. The hardness of the oxide is a factor of less importance.

However, at a later date, Bethune and Waterhouse (28) found that development of high adhesion between fretted surfaces coincided with low fatigue life, and with implications contrary to earlier conclusions, found that the contact of similar crystal structures, as for steel on steel, developed greater adhesion than did other combinations.

Liu, Corten and Sinclair (30) found that the hardness of the gripping material was an important variable.

> Fretting caused by gripping pads of hardness above the critical range [100 to 230 DPH], reduces the fretting fatigue strength to the range of 0.2 to 0.4 of the fatigue limit of the titanium alloy specimens. Gripping pads of low hardness, below the critical range, give fretting fatigue strengths above 0.8 of the fatigue limit of the specimen.

Waterhouse (36) considered that the fretting process could bring about work-hardening and recrystallization. If hardness was an important factor then actual hardness would not be as directly related to fretting fatigue performance as would the hardness in the fully annealed condition. He concluded, ". . . It would therefore not matter whether the material was in the annealed or work-hardened condition. . . ." By comparison, Sachs and Stefan (50) found that cold work and heat treatments not only affected the regular and chafing (as he called fretting in 1941) fatigue strengths, but that the effects were different.

> . . . Generally, annealed wrought metals have a higher chafing fatigue strength but a lower regular fatigue strength than the harder cold-worked and heat-treated conditions. Cast steels and aluminum alloys may have a

> higher chafing fatigue strength than wrought metals of the same type.

Frost (38) observed that the performance of various ferritic high tensile steels under the most severe fretting fatigue conditions was no better than the performance of mild steel. Harris (15) reported a similar lack of superior performance by alloys over their base metals. He attributed their apparent equivalence to the tendency of fretting fatigue tests to indicate crack propagation properties.

Oding and Ivanova (19) considered fatigue strength reduction under conditions of fretting fatigue to be the result of electric erosion which ". . . proceeds under the action of a thermoelectric current that is produced as a result of friction. . . ." Application of a counter current or the proper selection of materials would, they considered, effectively raise the fatigue strength. Stepanov and Terent'ev (51) similarly found that large reductions in fatigue strength correlated with large differences in contact potential, but that similar contact materials were slightly superior to identical contact materials. They recommended that

> . . . when titanium alloys are used in structures working under fretting conditions, the counterparts should be made of aluminum-base alloys or other metals (alloys) whose electronegativity approaches that of aluminium and titanium alloys.

2.5.10 Surface Treatment

While the effect of surface finish with respect to fretting fatigue is small, some surface treatments have proven to be beneficial. Horger (37) considered that little could be done to prevent the initiation of fatigue cracks, but that favourable residual stresses and geometry could help to prevent their propagation.

Liu, Corten and Sinclair (30) reported that shot-peening definitely improved fretting fatigue strength. With severe cold-rolling or shot-peening, Starkey, Marco and Collins (52) obtained not only higher values for the fretting indurance limit but also reduced scatter in their results.

Waterhouse, Brook and Lee (53) found electroplating to be relatively beneficial but the absolute effect depended on how the fatigue properties per se were affected.

> . . . The [fretting fatigue limit] is shown to be proportional to the square of the thickness of the coating for a particular metal. The overall effect of an electro-deposited coating depends on the balance between the reduction of fretting damage and the deleterious effects of plating on the fatigue strength of the steel. . . .

Waterhouse and Allery (54) reported that phosphate and sulphide-nitride coatings would increase the fretting fatigue strength of steel only if they were impregnated with a suitable oil-in-water emulsion. Waterhouse and Taylor (55) considered the reduction of fatigue strength by decarburization to be beneficial only in the sense that further reduction with the superposition of fretting was less than for normalization or cold-working.

2.6 Summary

The review of the fretting fatigue literature shows that generalization with respect to the effect of a specific variable is seldom possible. The opinions of many investigators are directly opposed even on fundamental aspects of the fretting-fatiguing mechanism(s). Where agreement does occur, the application of experimental findings to indeterminate service conditions is difficult.

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Introduction

The review of published literature in Chapter 2 indicates that while the results of some experiments are pertinent to the rate of development of damage, there have been no studies which specifically investigate cumulative damage under conditions of fretting fatigue.

This investigation was carried out to study the rate of development of fatigue damage when different conditions of simultaneous fretting, as defined by slip amplitude and normal load, are combined sequentially.

3.2 Test Program

A one-step fretting fatigue test was selected for this investigation because of: (a) its close similarity to service fretting conditions, and (b) a requirement for cumulative test results which could be compared to two-stage results obtained by previous investigators. The independent variables were slip amplitude and normal load; the dependent variable-cycles to failure.

The first objective was to determine the fatigue endurances which were characteristic of combinations of two levels of each independent variable (Section 3.5.3). Secondly, these combinations were paired to form cumulative tests: part way through a fretting fatigue test, either slip amplitude or normal load was changed to its alternate level. This adjustment was made at a chosen percentage of the characteristic life determined for the initial combination of variables. Cumulative tests were run employing the combinations in different orders and with change-over occurring at different chosen percentages (Section 3.6).

3.3 Material and Specimens

The material used was Ti-6AL-4V sheet. The manufacturer's specifications are given in Table 1. This alloy has been used by previous fretting fatigue investigators and has proven to be particularly susceptible to fretting damage. In industry, it is used extensively in airframe fuselage structures near engines and in aircraft gas-turbine compressors.

A direct stress fatigue specimen (Figure 3) was designed to have dimensions compatible with an Amsler High Frequency Vibrophore for this investigation, and with a low-temperature chamber for subsequent work.

The fatigue specimens were prepared in groups. Each group, or batch, of approximately 20 specimens was clamped into a pack and milled to the required dimensions. The specimens were then separated and polished in a longitudinal direction by moving them lightly against dry 220 and 400 grit silicon carbide waterproof paper clamped to a 3½ inch diameter drum rotating at 600 rpm. All machining burrs and surface marks which could be detected with a X10 magnifier were polished out,

TABLE 1

Specifications for Ti-6Al-4V Sheet

Supplier: Armco Steel Corporation

Thickness: 0.060 inches

Heat treatment: Annealed and pickled

Heat number: K00208

Chemical Analysis:	C	.025
	Fe	.14
	N	.012
	O	.16
	H	65 ppm.
	V	4.2
	Al	6.45
Mechanical Properties:	L	T
.2% Y.S. (psi)	132,100	165,500
U.T.S. (psi)	150,000	169,000
% elongation in 2 in.	9.0	10.0
Rockwell hardness	C36.0	C36.0

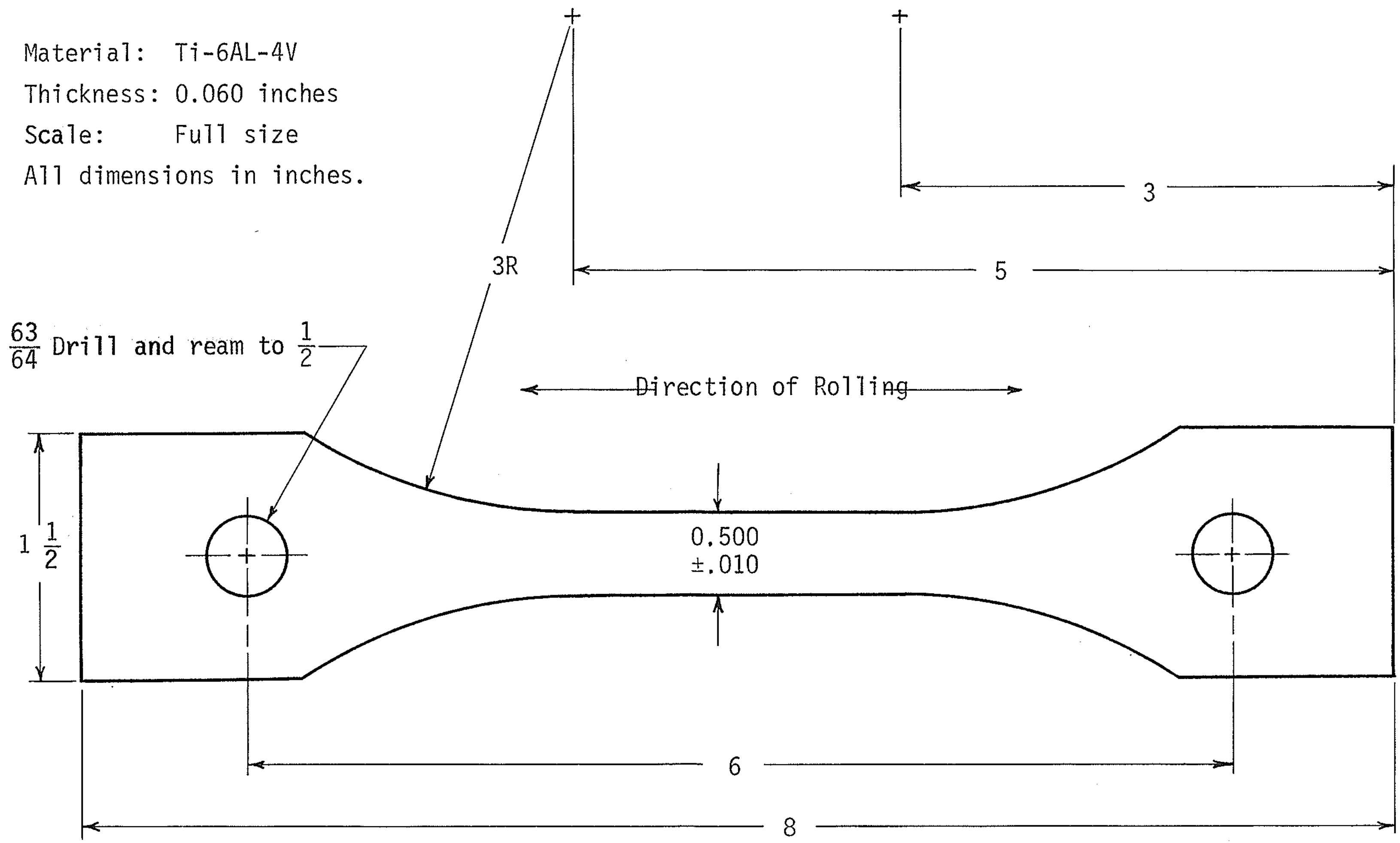


Figure 3. Fatigue Specimen

and the width of each specimen was measured with a micrometer at three positions in the parallel region. Each batch of specimens was then stress-relieved at 1000°F for two hours and air cooled. The oxide layer was removed by total immersion for two minutes in a pickling solution (by volume: H_2O, 65%; HF, 2%; HNO_3, 33%), and the specimens were stored in a plastic bag.

The fretting pads were made in strips of length 4½ inches and having 1/16 and 1/4 inch flats. Subsequent to stress-relieving and acid-cleaning, the strips were cut into 9/16 inch lengths.

Following the fretting fatigue test program the failed fatigue specimens were subjected to a Rockwell hardness test to investigate differentiation by virtue of their preparation in batches. The readings lay between R_C 34.3 and R_C 38.3, and the batches were assumed to have comprised a single population with respect to any possible differences in fatigue properties which might have been produced by their separate heat treatments.

An attempt to measure grain size was unsuccessful due to difficulty in finding an etchant which would permit clear observation of the grain boundaries.

3.4 Test Equipment

3.4.1 Fretting Apparatus

The fretting apparatus (Figures 4, 5 and 6) employs a bridge assembly which makes contact with the fatigue specimen at two points. Because the contact pressure is higher at the knife-edge than at the fretting pad, elongation and contraction of the fatigue specimen results in relative displacement, or slip, only at the interface of the fretting pad and the fatigue specimen. This slip amplitude is nominally a function of the adjustable contact separation and the amplitude of alternating fatigue stress.

3.4.2 Normal Load Clamp

The requirements for the normal load clamp were that it:

(a) exert a maximum normal load of 200 pounds without suffering permanent deformation (a magnitude which, applied to a contact area of 1/2 x 1/16 sq. in., was indicated in published reports as being sufficient for the development of significant damage),

(b) be removable from the fatigue specimen without necessitating removal of the specimen from the testing machine (in anticipation of further studies involving fatigue tests with intermittent fretting),

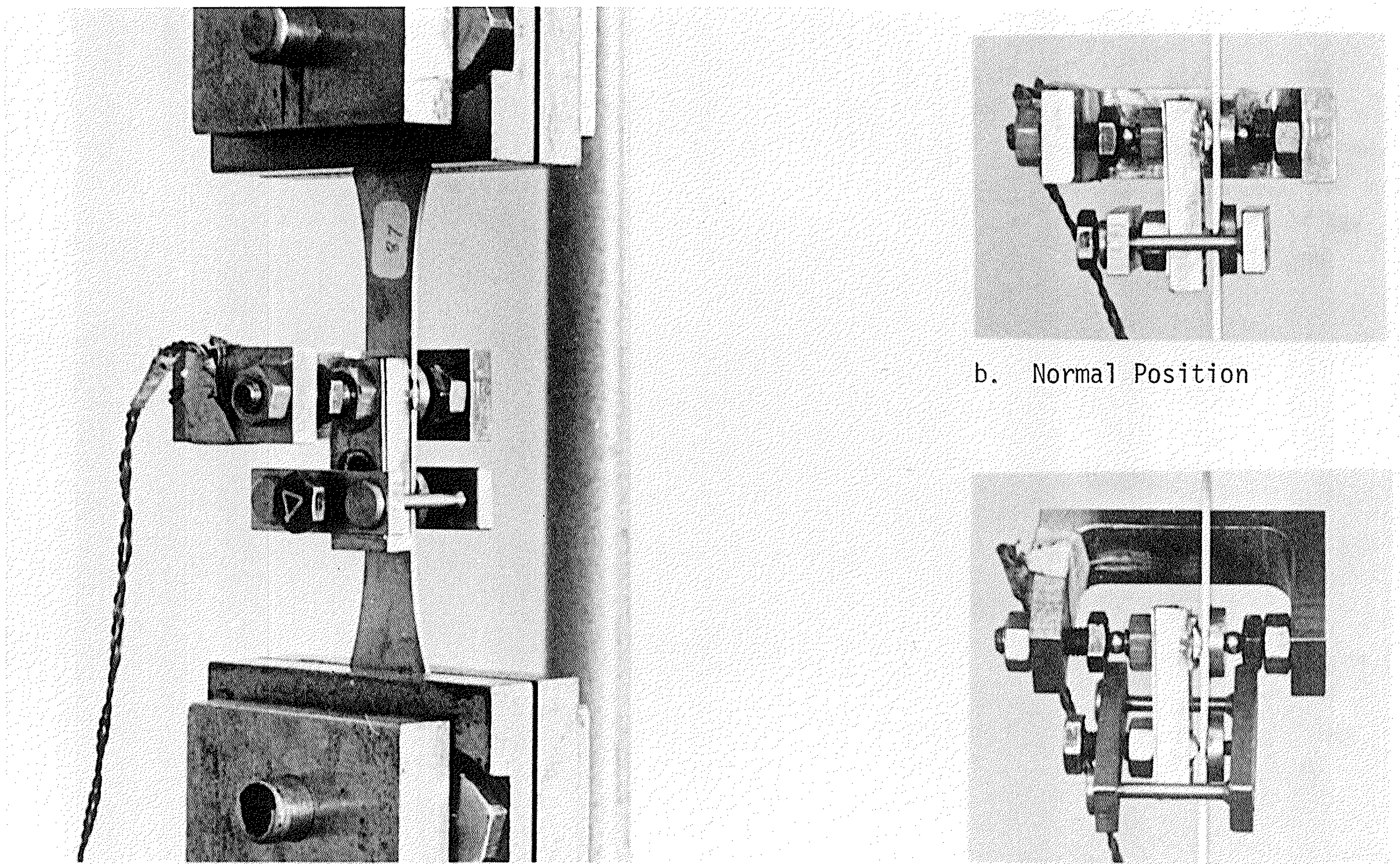
(c) possess maximum compliance consistent with other requirements being satisfied (to minimize readjustment of the normal load necessitated by wear or accumulation of debris at the fretting interface, or by realignment of the fretting apparatus),

(d) not cause appreciable transverse or torsional vibration (which would impede the operation of the testing machine),

(e) be self-aligning throughout a test,

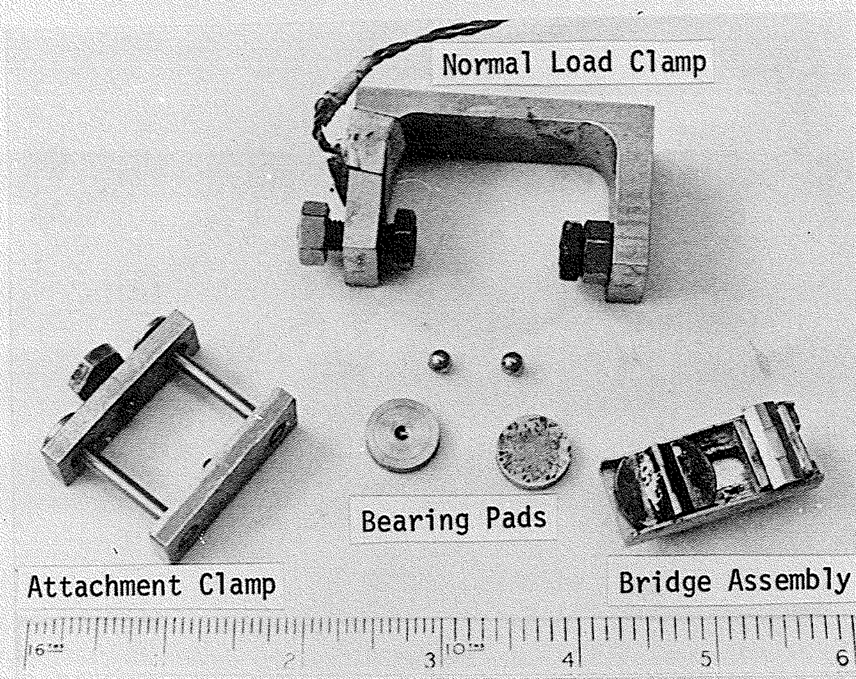
(f) provide a continuous indication of normal load, and

(g) be simply calibrated by dead weight.

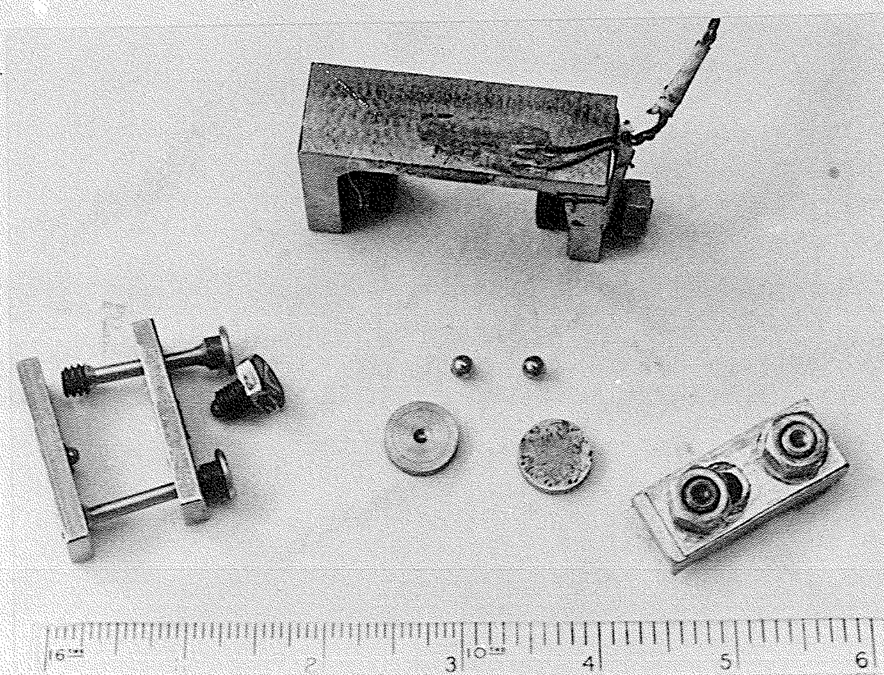


a. b. Normal Position c. Pivoted for Viewing

Figure 4. Fretting Apparatus Mounted on Fatigue Specimen



a.



b.

Figure 5. Components of Fretting Apparatus

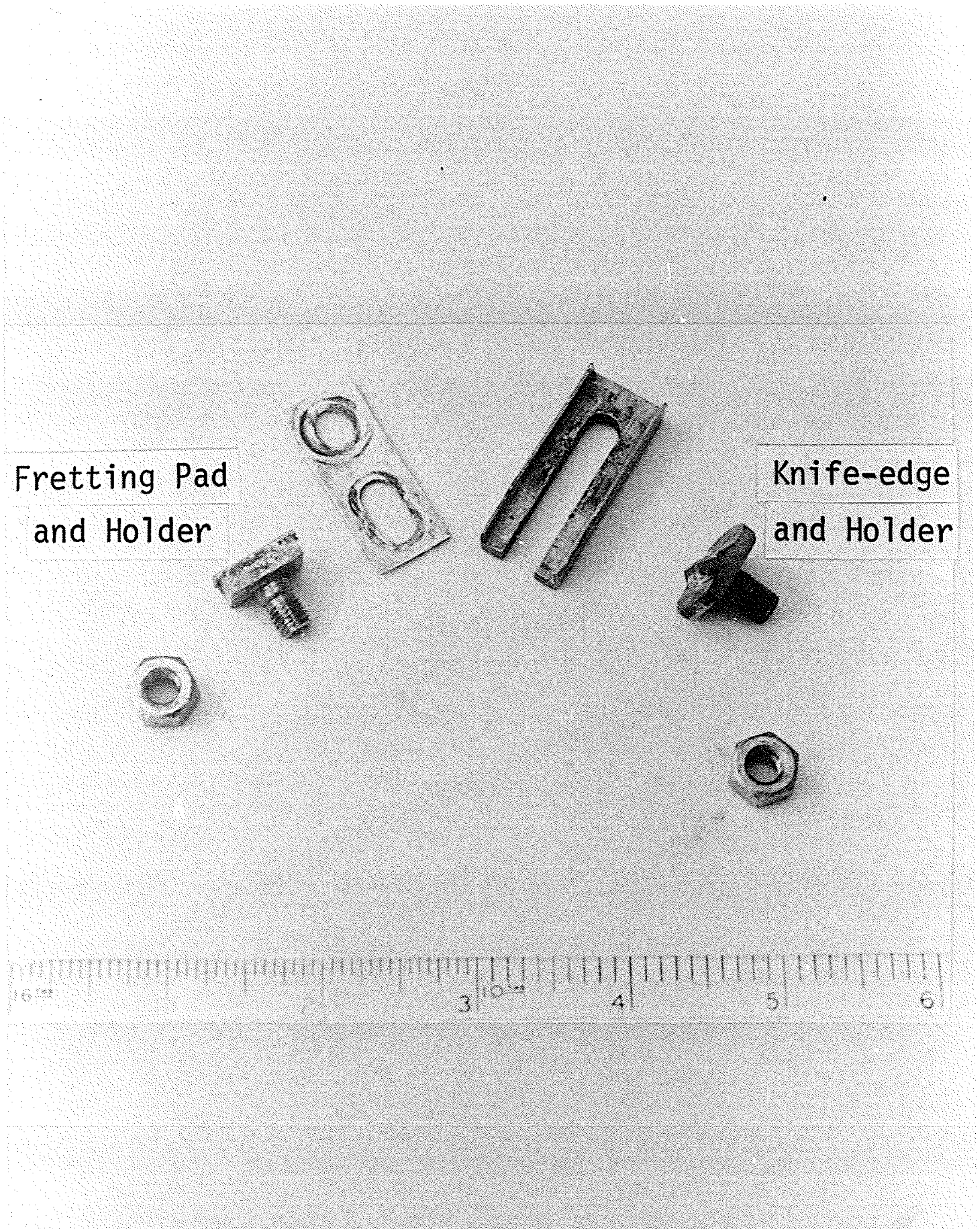


Figure 6. Components of Bridge Assembly

A C-configuration was selected and two mounted strain gauges were connected in half-bridge to be temperature-compensating and doubly sensitive to the large bending stress component.

The prototype of the normal load clamp is shown in Figure 7. Trimming the back face increased the compliance by a factor of 2 (determined by measuring the spreading of the arms with a vernier micrometer). Additional material was removed from the arms prior to using the clamp in the fretting fatigue tests.

The clamping load was simulated during calibration by employing the clamp as a connecting link between a support frame and a weight pan (Figure 8). The mean sensitivity of the clamp was 13.6 $\mu\varepsilon$ /lb for loads up to 200 pounds. The maximum variation in microstrain and in slope was 3.2% of reading and of mean slope respectively.

3.4.3 Knife-edge and Attachment Clamp

The requirements for the knife-edge and attachment clamp were that they:

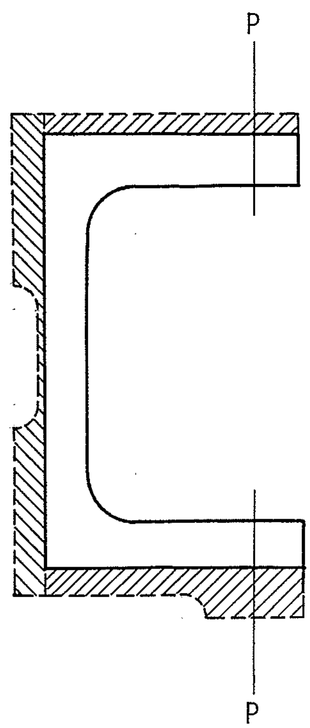
(a) anchor the bridge assembly to the fatigue specimen,

(b) not initiate failure at the knife-edge contact,

(c) permit adjustment of the contact separation without disturbing the fretting pad,

(d) not influence the calibrated clamping load applied to the fretting pad, and

(e) be self-aligning throughout a test.



= material removed from back face until onset of permanent spreading at 240 lb.

= additional material removed from arms

P = load axis

Figure 7. Maximization of Compliance of Normal Load Clamp

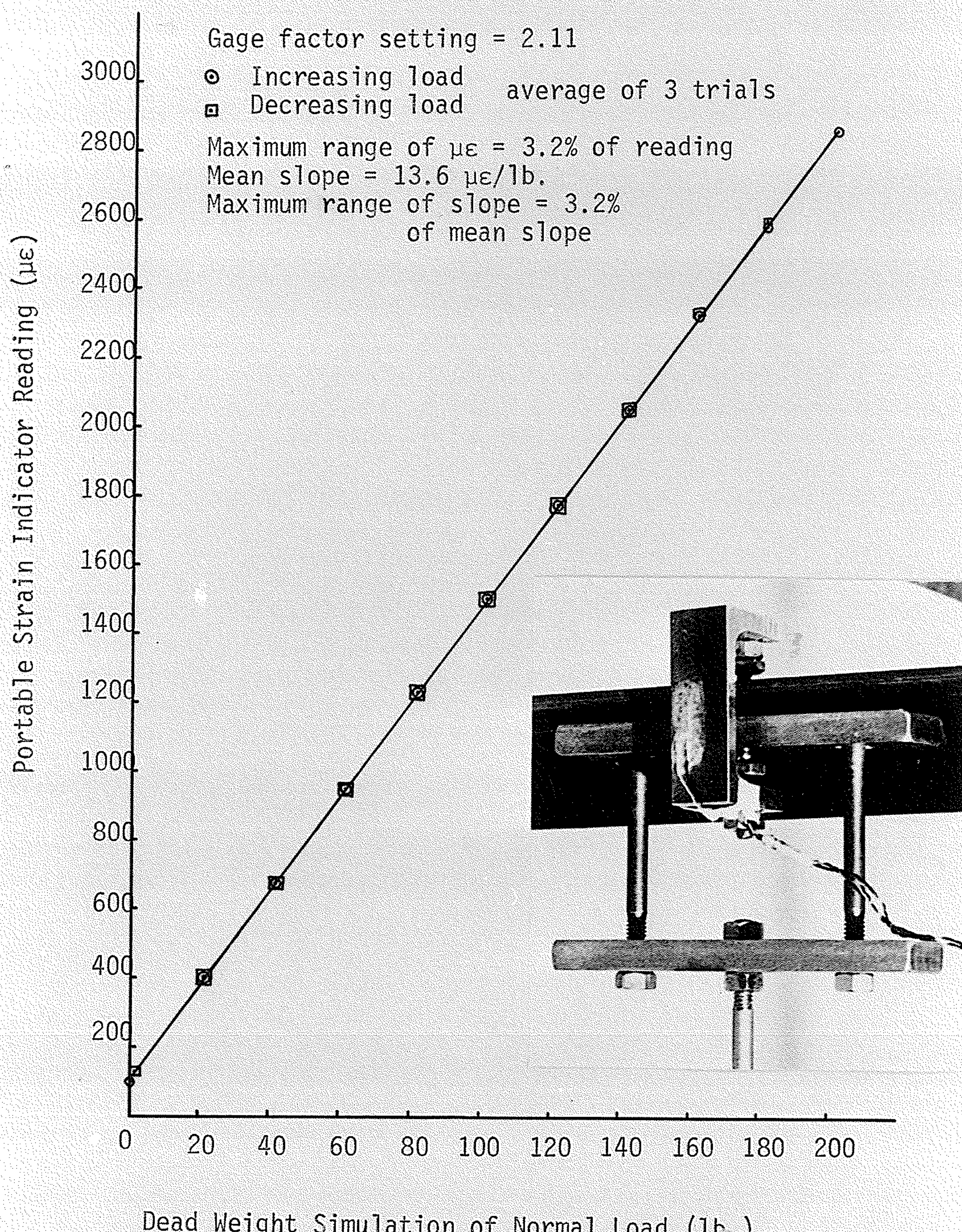


Figure 8. Calibration of Normal Load Clamp

The knife-edge was made by silver-soldering a length of tool steel, ground to a triangular cross-section, into a slot in a holder similar to that for the fretting pad (Figures 5a and 6). The edge was ground so that contact was made only over the center three-sixteenth inch of the fatigue specimen (Figure 9a).

Unsuccessful methods of attachment were:

(a) two hardened pins which screwed through a partially encircling bridge piece to indent the edges of the fatigue specimen,

(b) a single hardened point which centrally indented the same face of the fatigue specimen as was fretted, and

(c) a knife-edge which extended across the full width of the fatigue specimen.

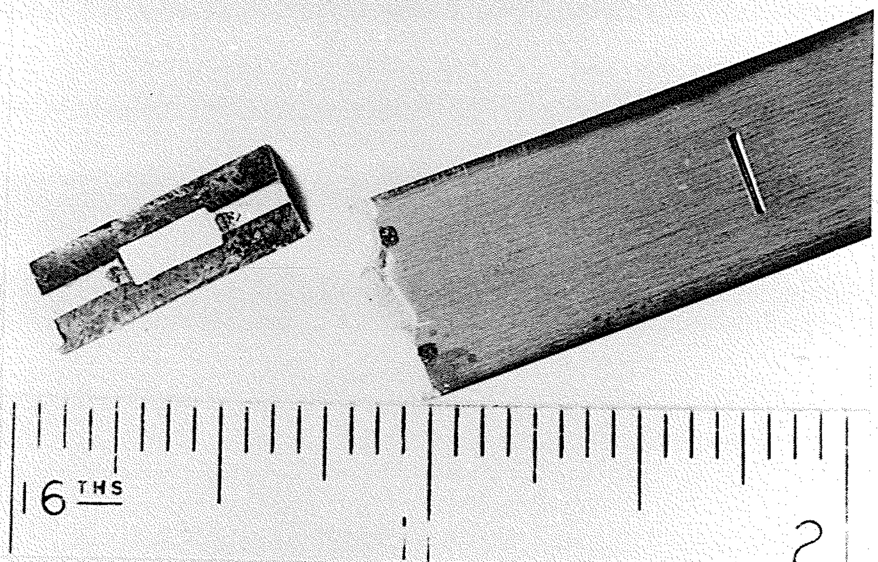
These methods tended to induce failure at the point of attachment rather than at the fretting scar.

3.5 Test Procedure

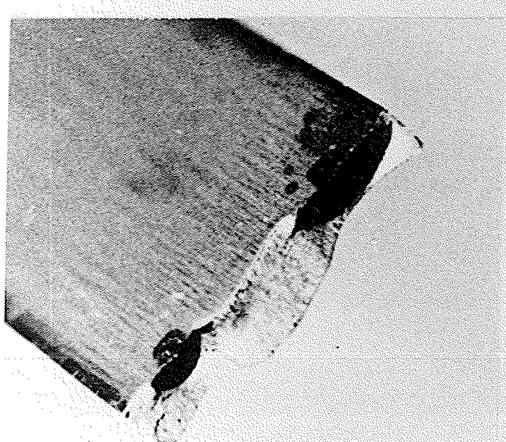
3.5.1 Calibration of Amsler Vibrophore

Before and after the fretting fatigue tests the Amsler Vibrophore was statically calibrated over its tensile load range. At each load level the change in error over the period of fatigue testing was less than the manufacturer's stated accuracy (± 1.5% or ± 11 lb). The maximum observed error was 1.8% of indicated load.

The calibration, as detailed in Appendix B, was accomplished by using a load transducer to compare the Amsler Vibrophore to a Baldwin-Tate-Emery universal testing machine which in turn was



a.



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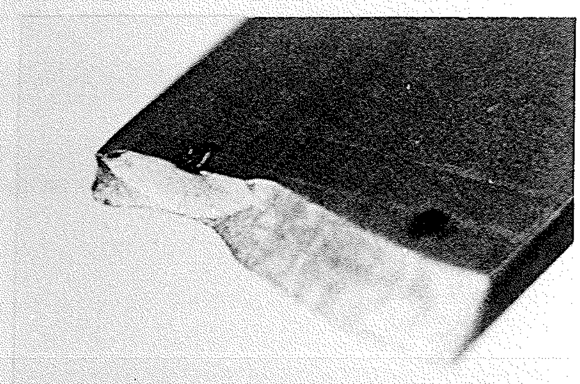

c.

Figure 9. Examples of Fretting Scars and Fracture Surfaces

calibrated with a certified proving ring.

3.5.2 General Setting-Up and Running Procedures

The normal load clamp was calibrated at the required load level(s) prior to each test. The fretting pad was cemented in the locating slot of its holder with Eastman 910 adhesive, and the center quarter-inch of the fretting contact face was filed down with the aid of a jig. After setting the contact separation and fitting the fretting apparatus to the fatigue specimen, the entire assemblage was mounted in the fatigue testing machine and the mean load applied. The normal load clamp was readjusted and the test begun by applying the alternating fatigue load.

In the cumulative tests the machine was stopped after the desired number of load cycles, either the normal load clamp or the contact separation adjusted to its new level, and the test continued until the fatigue specimen fractured.

At a constant frequency of 51 Hz, each test lasted typically about one-half hour. The continually changing damping characteristics of the fretting apparatus made it necessary to adjust the mean and alternating loads at irregular intervals to maintain the chosen nominal stresses. It was usually necessary to readjust the normal load clamp a couple of times during a test, that is, whenever the load indication changed by $\pm$ 10 $\mu\varepsilon$ ($\pm$ 0.74 lb) from the desired level. The ambient air temperature and relative humidity were determined prior to each test with the aid of a sling psychometer.

3.5.3 Preliminary Characteristic Life Tests

Exploratory tests were run with specimens #64 to #87 to study the effects of contact separation (slip amplitude) and normal load. Four combinations were selected from these results (Table 2) and their characteristic endurances determined by further testing (Tables 2 and 3).

The levels of nominal alternating and mean fatigue stresses, which were maintained throughout all the fretting fatigue tests at 37.5 and 40.8 Ksi respectively, were sufficient to bring about, in most cases, failure in the fretted region in less than 10^5 cycles.

3.6 Test Results

3.6.1 Cumulative Slip Results

Cumulative slip tests, with the contact separation being adjusted at 50% of the initial characteristic life, were carried out at normal loads of 82 and 102 pounds. Tests involving adjustment at 25% were performed at 102 pounds. At both percentages tests were done with the contact separation initially at the larger and at the smaller setting. The cumulative slip results are presented in Table 4.

3.6.2 Cumulative Load Tests

Cumulative load tests, with the normal load being adjusted at 50% of the initial characteristic life, were carried out at contact separations of 5/8 and 7/8 inches. Tests involving adjustment at 25% were performed at 7/8 inch. At both percentages tests were done with the normal load initially at the larger and at the smaller setting. The cumulative load results are presented in Table 5.

TABLE 2

Effect of
Normal Load and Slip Amplitude
on Cycles to Failure

	L= 5/8	L= 6/8	L= 7/8	L= 9/8
P= 62	66-F- 59 65-R- 64		67-R- 76	
P= 82	68-F- 33 84-F- 44 102-F- 64 88-F- 72 64-F- 86 107-F-109 105-R- 45 94-R-114	72-F- 48	127-F- 41 81-F- 44 111-F- 47 69-F- 64 106-F- 66 91-F-103 101-F-113 78-F-118 95-Q- 44 109-Q- 57 104-R-134	
P= 92	74-F- 51	75-R- 56	76-F- 40	
P=102	100-F- 37 86-F- 53 99-F- 64 90-F- 69 87-F- 80 108-F- 82 103-F- 87 85-R- 37 89-R- 40 70-R- 57 93-R- 64	73-F- 50	96-F- 33 71-F- 36 83-F- 42 77-F- 45 98-F- 45 97-F- 49 92-F- 60	79-F- 90
P=122			80-F- 36 82-F- 61	

P= clamping load in pounds
L= distance between knife-edge and centerline of fretting pad in inches

100-F- 37

Specimen Number

Location of failure
F = fretting scar
Q = parallel
R = radius

Kilocycles of
Load at failure

TABLE 3

Median Characteristic Lives of Fretting Levels

Test Level	Kilocycles at Failure	Median	Range
(82, 5/8)	33 44 64 72 86 109 114[1]	72.0	81
(82, 7/8)	41 44 47 64 66 103 113 118 134[1]	66.0	93
(102, 5/8)	37 53 64 69 80 82 87	69.0	50
(102, 7/8)	33 36 42 45 45 49 60	45.0	27

[1]Failed at radius

TABLE 4

Cumulative Slip Results

Test Level	Values of P and L	Kilocycles at Failure	Median	Range
Cumslip 1	P= 82 L= 5/8 for 36 kilocycles L= 7/8 to failure	46 52 74 82 142	74.0	96
Cumslip 2	P= 82 L= 7/8 for 42 kilocycles L= 5/8 to failure	50 64 75 82 91	75.0	41
Cumslip 3	P= 102 L= 5/8 for 34 kilocycles L= 7/8 to failure	54 56 60 71 76	60.0	22
Cumslip 4	P= 102 L= 7/8 for 22 kilocycles L= 5/8 to failure	40 45 52 56 59	52.0	19
Cumslip 5	P= 102 L= 5/8 for 17 kilocycles L= 7/8 to failure	31 53 60 72	56.5	41
Cumslip 6	P= 102 L= 7/8 for 11 kilocycles L= 5/8 to failure	37 49 54 60 66	54.0	29

TABLE 5

Cumulative Load Results

Test Level	Values of P and L	Kilocycles at Failure	Median	Range
Cump 1	L= 5/8 P= 82 for 36 kilocycles P= 102 to failure	52 68 71 83 100	71.0	48
Cump 2	L= 7/8 P= 82 for 42 kilocycles P= 102 to failure	47 58 67 70 87	67.0	40
Cump 3	L= 5/8 P= 102 for 34 kilocycles P= 82 to failure	45 55 56 59 103	56.0	58
Cump 4	L= 7/8 P= 102 for 22 kilocycles P= 82 to failure	38 38 47 48 107	47.0	69
Cump 5	L= 7/8 P= 82 for 21 kilocycles P= 102 to failure	24 28 52 53 60	52.0	36
Cump 6	L= 7/8 P= 102 for 11 kilocycles P= 82 to failure	42 51 60 61 62	60.0	20

CHAPTER 4

ANALYSIS OF RESULTS

4.1 The Implications of Scatter in the Life Values

The destructive nature of fatigue testing dictates that repeated measurement of endurance reflect variability due to loading, specimen preparation, and specimen selection (56, p. 395). Nevertheless, most of the scatter observed in fatigue life testing of metals is considered to be an inherent characteristic of the material (56, p. 396). This scatter is dependent upon the stress ratio and the magnitude and sequence of stress amplitude (56, p. 397). The forms of these fatigue life distributions are varied, but do occasionally approximate a logarithmic normal distribution (56, p. 396).

While the question of scatter and its associated distribution is seldom mentioned in the fretting fatigue literature, Starkey, Marco and Collins (41) assumed random sampling from normal populations and tested sufficient numbers of specimens to allow significant statistical inferences to be made at a 95 per cent confidence level. They found that fretting fatigue scatter was greater than fatigue scatter, and that the scatter increased as the fretting was made more severe.

The characteristic lives determined in this investigation (Table 3) suggest to the contrary that scatter decreases as the fretting is made more severe. This trend is compatible with the observation that scatter in fatigue life decreases as the stress amplitude (fretting-induced stress concentrations in this case) is made greater (56, p. 397).

The small sample sizes used in this investigation (four to nine specimens) do not permit assessment of the degree to which the data groups represent particular distributions. Consequently there can be no tests for statistical differences in sample means. Differences in sample performance are "suggestive" rather than statistically significant, but have nevertheless been considered to be the effects of changing the levels of the independent variables.

4.2 The Suggested Non-Cumulative Effects of Slip and Normal Load

The non-cumulative test results (Tables 2 and 3) suggest that slip and normal load are very interdependent. The effect of changing one of them is dependent upon the prevailing level of the other.

Increasing the contact separation from 5/8 to 7/8 inches (or the nominal slip amplitude from 0.0015 to 0.0021 inches as calculated in Appendix D) produced a noticeable reduction in endurance at a normal load of 102 pounds, but not at 82 pounds.

Increasing the normal load from 82 to 102 pounds (or the nominal contact pressure from 5.2 to 6.5 Ksi as calculated in Appendix D) produced a noticeable reduction in endurance at a contact separation of 7/8 inches, but not at 5/8 inches.

4.3 The Suggested Cumulative Effects of Slip and Normal Load

The cumulative tests (Tables 4 and 5) were analyzed (Tables 6 and 7) and the results plotted in Figures 10 and 11. In their interpretation, a low summation of cycle-ratios is considered to be detrimental and to be representative of rapid development of fatigue damage.

The predominant distinction which appears in Figures 10 and 11 is that between initial fretting at the mild and at the severe level. For cumulative testing with respect to both slip and normal load, damage accumulated more rapidly when the specimen was fretted initially at the severe level.

However, the difference in rate of damage for mild and severe initial levels depended on the initial stage cycle percentage in different ways for cumulative slip and load tests. For the cumulative slip tests, the difference produced by order of testing was large at small initial percentages. For the cumulative load tests, the difference was small at small initial percentages.

Cumulative testing involving fretting levels having approximately the same characteristic endurance, was not necessarily insensitive to the order of testing. Cumslip 1 and Cumslip 2 were conducted at fretting levels having characteristic lives of 72 and 66 kilocycles and there was no appreciable effect of order of testing. However, Cump 1 and Cump 3 were based on characteristic lines of 72 and 69 kilocycles, and the sequence effect was as large as any of the other cumulative tests.

TABLE 6

Analysis of Cumulative Slip Results

Test Level	Classification of Initial Stage[1]	Percentage of Characteristic Life during Initial Stage[2]	Summation of Cycle-Ratios[3]
Cumslip 1	mild	50%	1.076
Cumslip 2	severe	64%	1.095
Cumslip 3	mild	49%	1.070
Cumslip 4	severe	49%	0.924
Cumslip 5	mild	25%	1.124
Cumslip 6	severe	24%	0.868

[1]Each test level incorporates two different fretting conditions. The condition having the lower median characteristic life (refer to Table 3) is labelled "severe". There is no statistical basis for this distinction. For example, Cumslip 1 utilizes fretting conditions (82, 5/8) and (82, 7/8). As their respective median characteristic lives are 72 and 66 kilocycles, (82, 5/8) is labelled as "mild".

[2]Cumslip 1 called for 36 kilocycles at the initial condition, (82, 5/8). The percentage of characteristic life during the initial stage is: $\frac{36}{72} \times 100 = 50\%$.

[3]Refer to Appendix D for method of calculating summation of cycle-ratios.

TABLE 7

Analysis of Cumulative Load Results

Test Level	Classification of Initial Stage[1]	Percentage of Characteristic Life during Initial Stage[1]	Summation of Cycle-Ratios[1]
Cump 1	mild	50%	1.007
Cump 2	mild	64%	1.192
Cump 3	severe	49%	0.798
Cump 4	severe	49%	0.868
Cump 5	mild	32%	1.007
Cump 6	severe	24%	0.987

[1]Refer to footnotes in Table 6

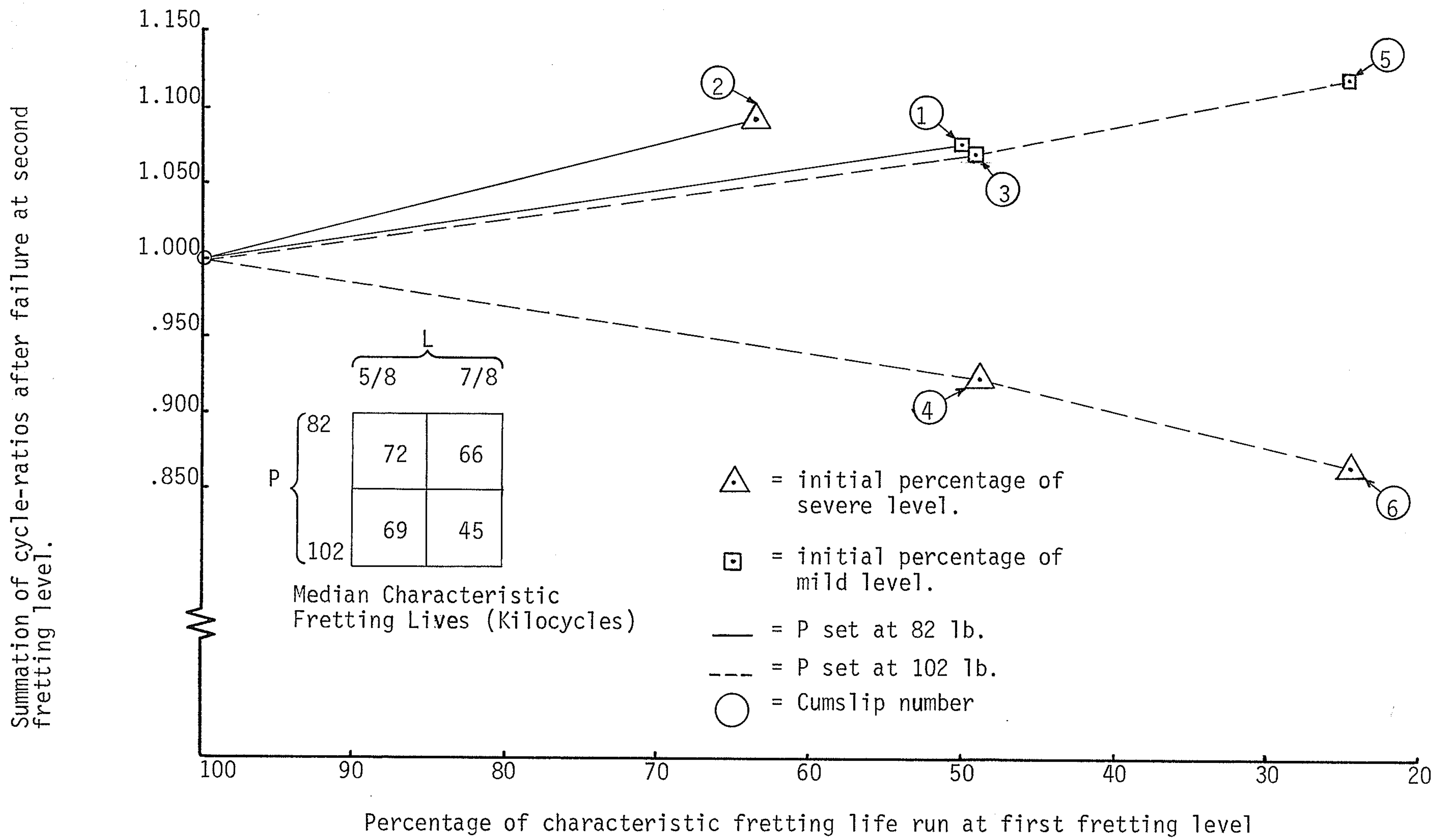

Figure 10. Cumulative Slip: Summation of Cycle-Ratios versus Percentage of Characteristic Life During Initial Stage.

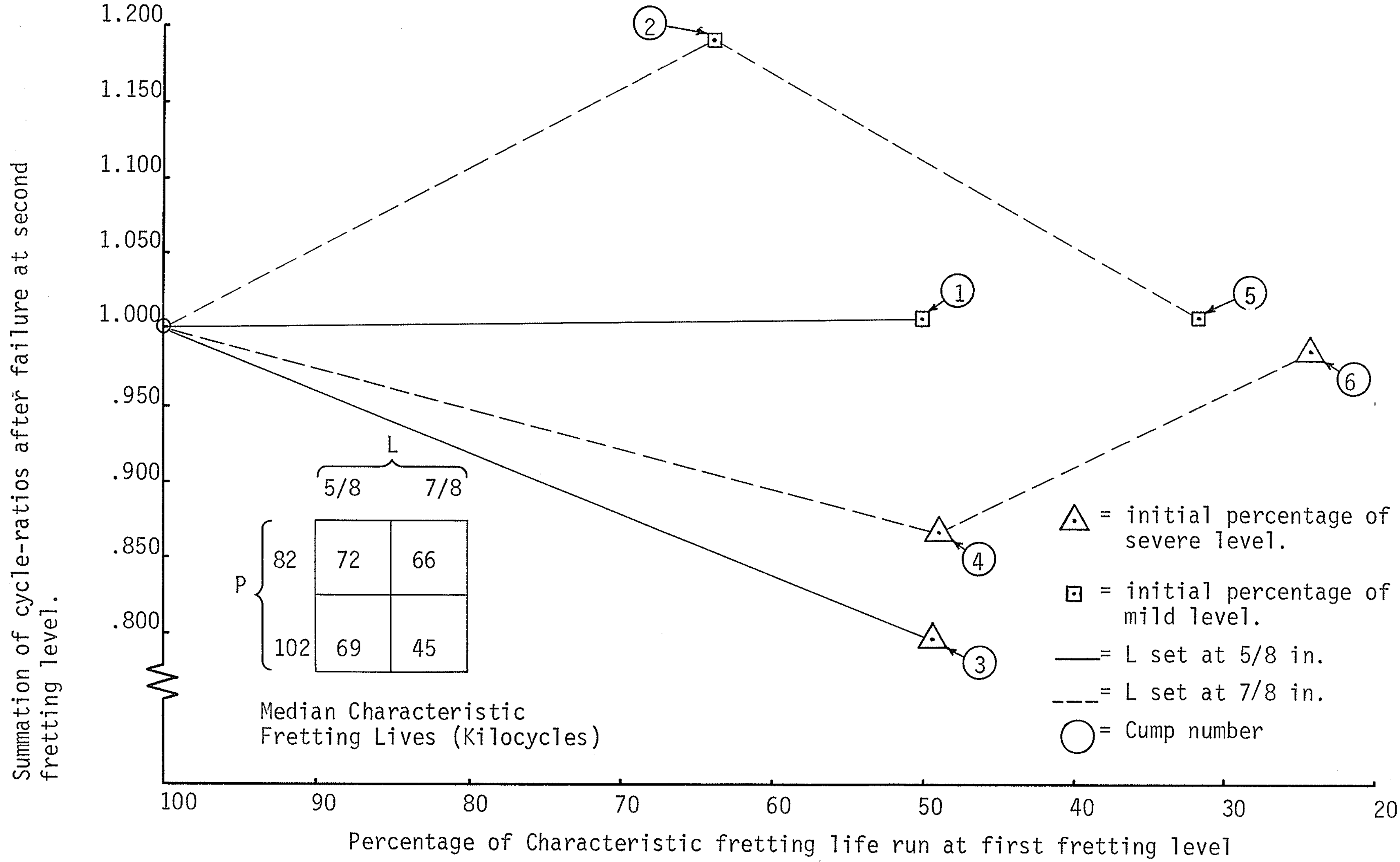

Figure 11. Cumulative Load: Summation of Cycle-Ratios versus Percentage of Characteristic Life During Initial Stage.

The effects of the order of testing and their further dependence on the percentage at the initial level do not suggest a particular correlation with the concept of early maximization of fretting damage as developed by previous investigators under conditions of two-stage testing.

4.4 Visual Interpretation of the Fretting Scar and Fracture Face

It can be seen in Figure 9 that there are two obvious points of crack initiation in the fretted region. In some cases the resultant fracture face passes through both initiation sites.

The actual contact area, as estimated from the area of discoloration, was typically one-quarter of the nominal contact area. A better estimate of the nominal contact pressures corresponding to 82 and 102 pounds is therefore 20 and 26 Ksi, assuming equal division of the normal load. This diminished contact area is a result of the convex surface produced by longitudinal polishing of the parallel region of the fatigue specimen.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

Conditions of fretting fatigue have been established in terms of nominal slip and normal pressure at the fretting interface. The severity of these conditions relative to each other have been determined from their characteristic endurances. Cumulative tests have been run by combining these conditions in different proportions and sequences, and the rates of development of fatigue damage have been inferred from the summation of cycle-ratios at failure.

5.2 Conclusions

The following behaviour is suggested by the results:

(a) Scatter in fatigue life decreases as conditions of fretting fatigue are made more severe.

(b) Slip and normal load are highly interdependent.

(c) Fatigue damage accumulates more rapidly when fretting fatigue occurs initially at a severe condition, as defined by either slip or normal load.

(d) The difference in fretting fatigue performance produced by testing sequence varies inversely with initial stage cycle percentage for cumulative slip testing, and directly for cumulative load testing.

(e) Cumulative testing at conditions having indistinguishable characteristic endurances can be highly sensitive to testing sequence.

5.3 Suggestions for Further Study

(a) Cumulative slip and load tests could be carried out with change-over occurring at percentages other than 25% and 50%.

(b) The numerical quantities required for calculation of the summation of cycle-ratios could be determined sequentially, thereby giving individual estimates of ratio summation in a manner suitable for statistical analysis of differences.

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APPENDIX A

Survey of Fretting Fatigue Investigations

NOTE: 1. Definitions of fretting fatigue limit

(a) Bethune (1965) - number of cycles of fretting below which a propagating fatigue crack is not initiated.

(b) Waterhouse (1962, 1964, 1965) - the maximum number of initial fretting fatigue cycles which do not significantly reduce the life of the specimen in a subsequent fatigue test.

Principal Author and Date	Bethune (57) 1965	Bowers (45) 1968	Collins (46) 1964	Collins (58) 1965	Corten (49) 1955	Fenner (59) 1956	Fenner (22) 1959	Field (23) 1963	Field (32) 1967	Field (47) 1968	Harris (34) 1967	Harris (15) 1970	Horger (37) 1953	Liu (30) 1957	Milestone (17) 1966	Nishioka (44) 1969a
TEST TYPE																
One-step		•			•	•		•	•	•	•	•	•	•		•
Two-step	•		•	•			•	•	•						•	
Static pre-fret ($\sigma_a=0$)			•	•				•								
Dynamic pre-fret ($\sigma_a \neq 0$)	•						•		•						•	
GENERAL DESCRIPTION																
Direct stress		•	•	•		•	•	•	•	•	•	•				
Bending stress	•	•			•								•	•	•	•
Alternating stress ($\sigma m=0$)	•		•	•	•								•	•	•	•
Fluctuating stress ($\sigma m \neq 0$)		•				•		•	•	•	•	•				
Joint arrangement					•						•			•		
Press-fit arrangement													•			
INPUT VARIABLES STUDIED																
Slip amplitude		•	•	•			•		•	•						•
Clamping pressure		•	•	•	•	•					•	•	•	•	•	
Alternating stress						•	•				•					•
Mean stress			•	•			•		•	•						
Atmosphere							•							•		
Relative humidity																
Specimen bulk temperature																
Material		•			•							•	•	•	•	
Heat treatment					•							•	•	•		
Surface preparation											•	•	•	•	•	
Geometry													•			
Clamping conditions									•	•						
Contact potential difference																
Direction of fretting								•								
OUTPUT VARIABLES STUDIED																
Endurance						•	•									
Fatigue strength		•	•	•	•			•	•	•	•	•	•	•	•	•
Fretting fatigue limit	•															
Prot failure stress																
Microscopic examination							•				•					•
Adhesion force	•															
Friction force															•	
Thermo-electric current																
Interface electrical resistance															•	
Microhardness	•				•											
Profilometer																

Principal Author and Date	Nishioka (29,43) 1969b	Nishioka (26) 1969c	Oding (19) 1956	Pavliscak (16) 1968	Rimbey (60) 1967	Sachs (50) 1941	Starkey (41) 1957	Stepanov (51) 1968	Warlow-Davies (14) 1941	Waterhouse (31) 1961	Waterhouse (53) 1962	Waterhouse (36) 1964	Waterhouse (54) 1965	Waterhouse (35) 1971a	Waterhouse (55) 1971b	Wright G.P. (61) 1970
TEST TYPE																
One-step	•	•	•	•	•	•		•						•	•	•
Two-step							•		•	•	•	•	•			•
Static pre-fret (σ_a=0)									•							•
Dynamic pre-fret ($\sigma_a \neq 0$)							•			•	•	•	•			
GENERAL DESCRIPTION																
Direct stress					•											•
Bending stress	•	•	•	•		•	•	•	•	•	•	•	•	•	•	
Alternating stress (σ_m=0)	•		•	•		•	•	•	•	•	•	•	•	•	•	•
Fluctuating stress ($\sigma_m \neq 0$)		•			•											
Joint arrangement							•									•
Press-fit arrangement				•		•										
INPUT VARIABLES STUDIED																
Slip amplitude	•															•
Clamping pressure				•	•											
Alternating stress	•	•	•	•	•											
Mean stress		•			•											
Atmosphere			•													
Relative humidity					•											
Specimen bulk temperature				•												
Material	•	•	•	•		•	•	•	•			•				
Heat treatment	•	•				•									•	
Surface preparation				•			•				•		•			
Geometry																•
Clamping conditions																
Contact potential difference								•								
Direction of fretting																
OUTPUT VARIABLES STUDIED																
Endurance										•	•		•			
Fatigue strength			•	•	•	•		•	•						•	•
Fretting fatigue limit											•	•	•			
Prot failure stress							•									
Microscopic examination	•	•								•	•	•		•		
Adhesion force																
Friction force	•															
Thermo-electric current			•													
Interface electrical resistance																
Microhardness																
Profilometer														•		

APPENDIX B

Static Load Calibration
of
Amsler High Frequency Vibrophore

Static Load Calibration of Amsler High Frequency Vibrophore[1]

Indicated Load (lb)	Pre-test Calibration: Load Cell Calibrated Reading[2] (με)	Pre-test Calibration: Load Cell Reading in Amsler[3] (με)	Pre-test Calibration: Amsler Error[6] (lb)	Post-test Calibration: Load Cell Calibrated Reading[4] (με)	Post-test Calibration: Load Cell Reading in Amsler[5] (με)	Post-test Calibration: Amsler Error[6] (lb)
500	441	447	+ 9	448	454	+ 9
1000	780	784	+ 6	795	797	+ 3
1500	1117	1129	+ 3	1134	1142	+12
2000	1458	1467	+13	1474	1485	+16
2500	1801	1810	+13	1818	1829	+16
3000	2142	2149	+10	2159	2167	+12
3500	2486	2489	+ 4	2506	2510	+ 6
4000	2830	2827	- 4	2850	2849	- 1

Maximum percentage error of Amsler under static tensile loading = $\frac{9}{500} \times 100 = 1.8\%$

Maximum increase in error between calibrations = $\frac{12 - 3}{1500} \times 100 = 0.6\%$

Manufacturer's stated accuracy of dynamometer = ± 1.5% or ± 11 lb.

[1] Serial No. 422/541; 2 Ton Dynamometer Type 10 HFP 422.
[2] Average of 6 trials. Maximum range = 2.3% of average.
[3] Average of 6 trials. Maximum range = 0.67% of average.
[4] Average of 4 trials. Maximum range = 1.3% of average.
[5] Average of 5 trials. Maximum range = 1.1% of average.
[6] Load cell conversion factor: 1 με = 1.453 lb.

APPENDIX C

Specimen Test Records

NOTE:

1. Nominal fatigue stresses for all tests were $\sigma_m = 40.8$ Ksi; $\sigma_a = \pm 37.5$ Ksi
2. Test frequency = 51 Hz.
3. Specimens within each prepared batch were randomly allocated to the test levels in progress.
4. Tests were run in sequence of increasing specimen number (except #64 which follows #76).
5. Test level acronyms:
   (P,L) = (normal load in pounds, contact separation in inches)
   Cumslip = cumulative slip test
   Cump = Cumulative load test

Specimen Test Records

Specimen Number	Batch	Parallel Width (inches)			D.B. (^oF)	R.H. (%)	Test Level	Failure Location	Kilocycles at Failure	Rockwell C Hardness	
64	4	.500	.502	.505	74	96	(82, 5/8)	Fret	86	36.2	36.4
65	4	.509	.512	.505	74	85	(62, 5/8)	Radius	64	37.3	37.8
66	4	.503	.505	.505	74	96	(62, 5/8)	Fret	59	35.8	36.5
67	4	.500	.500	.500	70	78	(62, 7/8)	Radius	76	36.4	37.2
68	4	.490	.493	.495	74	74	(82, 5/8)	Fret	33	38.1	38.1
69	4	.487	.489	.492	75	78	(82, 7/8)	Fret	64	38.2	38.3
70	4	.494	.493	.491	73	67	(102, 5/8)	Radius	57	36.2	36.8
71	4	.495	.491	.489	74	78	(102, 7/8)	Fret	36	36.3	36.5
72	4	.499	.496	.494	73	82	(82, 6/8)	Fret	48	35.8	36.1
73	4	.493	.490	.489	75	78	(102, 6/8)	Fret	50	36.6	36.9
74	4	.495	.495	.493	75	76	(92, 5/8)	Fret	51	35.4	36.8
75	4	.494	.496	.496	76	78	(92, 6/8)	Radius	56	37.1	37.4
76	4	.497	.497	.497	75	74	(92, 7/8)	Fret	40	-	-
77	5	.503	.505	.505	75	92	(102, 7/8)	Fret	45	37.7	38.2
78	5	.500	.502	.505	76	94	(82, 7/8)	Fret	118	36.0	37.3
79	5	.500	.499	.498	75	85	(102, 9/8)	Fret	90	35.6	35.8
80	5	.501	.499	.497	74	86	(122, 7/8)	Fret	36	36.3	36.8
81	5	.498	.500	.501	73	93	(82, 7/8)	Fret	44	35.8	37.5
82	5	.503	.502	.501	76	90	(122, 7/8)	Fret	61	35.8	37.4
83	5	.501	.501	.502	76	87	(102, 7/8)	Fret	42	36.2	36.5
84	5	.504	.502	.501	74	84	(82, 5/8)	Fret	44	36.9	37.2
85	5	.511	.510	.509	75	91	(102, 5/8)	Radius	37	36.8	37.6
86	5	.497	.500	.502	74	92	(102, 5/8)	Fret	53	35.7	36.4
87	5	.505	.503	.502	73	96	(102, 5/8)	Fret	80	36.2	36.3
88	5	.503	.506	.506	74	80	(82, 5/8)	Fret	72	36.1	36.2
89	5	.510	.510	.509	76	86	(102, 5/8)	Radius	40	35.4	35.5
90	5	.502	.504	.505	75	85	(102, 5/8)	Fret	69	36.6	37.3

Specimen Number	Batch	Parallel Width (inches)			D.B. (^{o}F)	R.H. (%)	Test Level	Failure Location	Kilocycles at Failure	Rockwell C Hardness	
91	5	.507	.508	.507	76	75	(82, 7/8)	Fret	103	36.4	37.4
92	5	.501	.500	.498	73	76	(102, 7/8)	Fret	60	35.4	36.8
93	5	.507	.506	.505	74	68	(102, 5/8)	Radius	64	36.2	36.8
94	5	.504	.504	.504	74	80	(82, 5/8)	Radius	114	35.8	36.8
95	5	.506	.505	.504	74	80	(82, 7/8)	Parallel	44	36.3	37.4
96	5	.504	.506	.505	74	82	(102, 7/8)	Fret	33	-	-
97	6	.494	.494	.494	75	91	(102, 7/8)	Fret	49	36.0	36.2
98	6	.493	.494	.493	74	88	(102, 7/8)	Fret	45	36.5	37.1
99	6	.496	.496	.495	75	87	(102, 5/8)	Fret	64	35.2	35.6
100	6	.494	.494	.494	73	91	(102, 5/8)	Fret	37	-	-
101	6	.500	.499	.498	74	87	(82, 7/8)	Fret	113	35.7	35.8
102	6	.495	.498	.497	73	86	(82, 5/8)	Fret	64	36.3	36.3
103	6	.501	.500	.502	74	85	(102, 5/8)	Fret	87	35.5	36.4
104	6	.495	.495	.495	72	78	(82, 7/8)	Radius	134	35.8	36.0
105	6	.496	.496	.496	73	91	(82, 5/8)	Radius	45	36.0	36.3
106	6	.496	.495	.495	73	88	(82, 7/8)	Fret	66	36.2	36.2
107	6	.491	.490	.493	72	86	(82, 5/8)	Fret	109	36.2	36.8
108	6	.493	.491	.489	73	84	(102, 5/8)	Fret	82	35.7	36.2
109	6	.491	.491	.489	72	78	(82, 7/8)	Parallel	57	35.6	35.7
110	6	.490	.489	.487	74	76	Cumslip 1	Fret	82	36.4	36.4
111	6	.492	.493	.492	73	91	(82, 7/8)	Fret	47	35.8	37.4
112	6	.489	.490	.490	75	78	Cumslip 3	Fret	56	35.2	35.6
113	6	.490	.489	.488	75	82	Cumslip 4	Fret	59	37.2	38.3
114	6	.486	.487	.488	75	82	Cumslip 2	Fret	82	35.4	35.5
115	6	.488	.489	.490	76	74	Cumslip 1	Fret	142	36.7	37.4
116	6	.490	.490	.489	72	83	Cumslip 4	Fret	45	-	-
117	7	.490	.492	.493	75	82	Cumslip 1	Radius	45	36.0	37.2
118	7	.492	.492	.493	74	87	Cumslip 3	Fret	71	36.3	36.3
119	7	.488	.489	.492	75	85	Cumslip 4	Fret	40	35.5	35.7
120	7	.491	.491	.490	74	81	Cumslip 3	Fret	54	35.3	35.4
121	7	.489	.492	.495	73	91	Cumslip 1	Fret	74	35.8	36.0
122	7	.498	.497	.496	73	86	Cumslip 4	Fret	52	35.2	35.4

Specimen Number	Batch	Parallel Width (inches)			D.B. (^{o}F)	R.H. (%)	Test Level	Failure Location	Kilocycles at Failure	Rockwell C Hardness	
123	7	.487	.487	.488	74	70	Cumslip 2	Fret	91	34.3	34.8
124	7	.497	.498	.498	73	78	Cumslip 1	Fret	52	35.3	36.0
125	7	.497	.497	.498	73	68	Cumslip 3	Fret	76	37.6	37.7
126	7	.497	.496	.497	73	60	Cumslip 3	Fret	60	35.8	36.2
127	7	.498	.497	.497	75	78	(82, 7/8)	Fret	41	-	-
128	7	.497	.498	.498	75	74	Cumslip 4	Fret	56	36.3	37.2
129	7	.503	.504	.503	72	82	Cumslip 2	Fret	75	35.9	37.0
130	7	.501	.500	.500	74	78	Cumslip 2	Fret	64	36.2	36.8
131	7	.501	.501	.501	74	84	Cumslip 1	Fret	46	36.8	37.4
132	7	.503	.502	.501	74	88	Cumslip 2	Fret	50	35.7	36.8
133	7	.497	.497	.497	72	80	Cump 1	Fret	83	36.2	36.8
134	7	.495	.493	.492	73	75	Cump 3	Fret	45	36.8	36.8
135	7	.497	.497	.500	74	71	Cump 2	Fret	67	37.8	38.0
136	7	.495	.495	.496	74	78	Cump 2	Fret	47	35.4	35.5
137	8	.504	.504	.503	75	74	Cump 2	Fret	38	-	-
138	8	.505	.505	.505	74	74	Cump 1	Fret	52	35.7	36.4
139	8	.496	.496	.496	75	70	Cump 4	Fret	38	35.2	35.4
140	8	.508	.507	.508	75	74	Cump 4	Fret	47	34.7	35.2
141	8	.499	.498	.497	75	74	Cump 3	Fret	56	36.5	37.2
142	8	.510	.511	.511	75	80	Cump 4	Fret	38	36.3	36.8
143	8	.509	.508	.508	75	72	Cump 3	Fret	103	35.3	36.8
144	8	.501	.502	.501	76	78	Cump 1	Fret	71	36.5	36.7
145	8	.499	.498	.497	75	74	Cump 4	Fret	48	36.8	36.8
146	8	.504	.503	.504	76	74	Cump 3	Fret	55	35.7	35.8
147	8	.507	.507	.507	75	74	Cump 4	Fret	107	35.5	35.7
148	8	.508	.507	.507	76	70	Cump 1	Fret	68	35.9	36.2
149	8	.504	.505	.507	74	73	Cump 2	Fret	42	36.6	36.7
150	8	.504	.503	.502	74	66	Cump 2	Fret	39	35.2	36.2
151	8	.491	.491	.492	72	77	Cump 3	Fret	59	36.7	36.8
152	8	.500	.502	.501	74	70	Cump 1	Fret	100	35.0	35.8
153	8	.502	.502	.503	74	64	Cump 2	Fret	87	36.3	37.2
154	8	.502	.503	.504	74	63	Cump 2	Fret	70	36.8	37.2

Specimen Number	Batch	Parallel Width (inches)			D.B. (^{o}F)	R.H. (%)	Test Level	Failure Location	Kilocycles at Failure	Rockwell C Hardness	
155	8	.502	.502	.503	74	62	Cump 2	Fret	58	35.8	36.8
156	8	.501	.501	.501	74	66	Cump 5	Fret	52	35.5	36.2
157	9	.511	.511	.510	74	60	Cump 6	Fret	62	35.8	36.0
158	9	.510	.510	.510	72	75	Cump 6	Fret	61	36.8	37.2
159	9	.509	.510	.510	73	70	Cump 5	Fret	20	35.0	35.4
160	9	.510	.511	.511	73	70	Cump 6	Fret	42	37.0	37.2
161	9	.511	.511	.511	75	68	Cump 5	Fret	60	35.4	35.6
162	9	.508	.510	.510	74	68	Cump 5	Fret	28	36.8	37.4
163	9	.512	.511	.512	74	62	Cump 6	Fret	60	35.3	36.2
164	9	.512	.512	.511	74	69	Cump 5	Fret	53	35.6	35.7
165	9	.518	.517	.515	74	70	Cump 6	Fret	51	35.7	36.9
166	9	.510	.509	.508	74	72	Cump 5	Fret	24	35.5	36.2
167	9	.509	.510	.511	74	66	Cumslip 5	Fret	31	-	-
168	9	.509	.508	.508	74	68	Cumslip 6	Fret	37	35.2	36.2
169	9	.510	.510	.509	74	64	Cumslip 6	Fret	54	36.2	36.7
170	9	.508	.508	.507	72	71	Cumslip 6	Fret	66	35.3	37.2
171	9	.506	.506	.507	74	68	Cumslip 5	Fret	53	35.4	35.5
172	9	.510	.510	.510	74	68	Cumslip 5	Fret	72	34.9	35.8
173	9	.505	.503	.502	74	68	Cumslip 5	Radius	52	34.8	36.3
174	9	.507	.508	.508	74	65	Cumslip 5	Fret	60	-	-
175	9	.508	.507	.506	74	68	Cumslip 6	Fret	49	37.0	37.8
176	9	.505	.504	.505	74	67	Cumslip 6	Fret	60	36.7	37.4

APPENDIX D

Sample Calculations

1. Calculations of Nominal Slip Amplitude

Assumptions:

a) No slip takes place between the knife-edge and the fatigue specimen.

b) The longitudinal strain in the parallel section is uniform and dependent only on the nominal alternating stress.

c) This longitudinal strain acting over the contact separation results in uniform slip over the fretting interface.

d) There is no elastic absorption of this uniform relative displacement either at the fretting interface or in the bridge assembly.

$$S_a = \frac{(\sigma_a)\,(L)}{E}$$

S_a = nominal slip amplitude (in.)
σ_a = nominal alternating stress amplitude = 37,500 psi
L = contact separation (in.)
E = modulus of elasticity for Ti-6Al-4V = 16×10^6 psi

when $L = 5/8$ in.

$$S_a = \frac{(37{,}500)(5/8)}{(16 \times 10^6)} = \pm\ 0.0015 \text{ in.}$$

when $L = 7/8$ in.

$$S_a = \frac{(37{,}500)(7/8)}{(16 \times 10^6)} = \pm\ 0.0021 \text{ in.}$$

2. Calculation of Nominal Contact Pressure[1]

Normal load = 82 lb.

Width of contact strip on fretting pad = 1/16 in.
Length of contact strip on fretting pad filed away = 1/4 in.
Width of parallel section of fatigue specimen = 1/2 in.

Nominal contact area = $(\frac{1}{16} \times \frac{1}{2}) - (\frac{1}{16} \times \frac{1}{4}) = \frac{1}{64}$ sq. in.

Nominal contact pressure at a normal load of 82 lb. $= \frac{82}{1/64} = 5.2$ Ksi.

Nominal contact pressure at a normal load of 102 lb. $= \frac{102}{1/64} = 6.5$ Ksi.

[1] The machined dimensions of the components in contact at the fretting location are used to determine nominal contact area in this calculation. See Section 4.4 for a better approximation of the contact area.

3. <u>Calculation of Summation of Cycle-Ratios at Failure by Linear Damage Rule</u>

$$SCR = \frac{N_o}{N_1} + \frac{N_2}{N_3}$$

SCR = Summation of cycle-ratios
N_o = Number of cycles run at first fretting level
N_1 = Median cycles to failure at first fretting level
N_2 = Number of cycles run at second fretting level
N_3 = Median cycles to failure at second fretting level

a. Cumulative Slip Test.

Cumslip 1: P = 82
(from Table 4) L = 5/8 for 36 kilocycles
L = 7/8 to failure at 74 kilocycles (median)

N_o = 36 Kilocycles
N_1 = Characteristic median life for (82, 5/8) from Table 3 = 72 Kilocycles
N_2 = 74 - 36 = 38 Kilocycles
N_3 = Characteristic median life for (82, 7/8) from Table 3 = 66 Kilocycles

$$SCR = \frac{36}{72} + \frac{38}{66} = 0.500 + 0.576 = 1.076$$

b. Cumulative Load Test.

Cump 1: L = 5/8
(from Table 5) P = 82 for 36 Kilocycles
P = 102 to failure at 71 Kilocycles (median)

N_o = 36 Kilocycles
N_1 = (82, 5/8) = 72 Kilocycles
N_2 = 71 - 36 = 35 Kilocycles
N_3 = (102, 5/8) = 69 Kilocycles

$$SCR = \frac{36}{72} + \frac{35}{69} = 0.500 + 0.507 = 1.007$$