NASA TECHNICAL MEMORANDUM

NASA TM X-71606

NASA TM X-71606

FRETTING IN AIRCRAFT TURBINE ENGINES

by Robert L. Johnson and Robert C. Bill
Lewis Research Center
Cleveland, Ohio 44135

TECHNICAL PAPER proposed for presentation at
Specialists Meeting on Friction and Wear in
Aircraft Systems sponsored by AGARD
Munich, Germany, October 11-12, 1974

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NASA-Lewis Research Center
Cleveland, Ohio 44135
U.S.A.

ABSTRACT

A review of experience shows that fretting is a continuing concern. Further, it is likely the problem will be more severe in new engines as a result of design trends. Critical fretting can occur on fan, compressor, and turbine blade mountings; also, on splines, rolling element bearing races, and secondary sealing elements of face type seals. Clamping devices, dampers, static seals flexible mountings, turbine combustor slip joints and other engine parts frequently show fretting. Structural fatigue failures can originate at fretted areas on component parts. Methods used by designers and maintenance groups to mitigate fretting are given; some newer recommended approaches are discussed. Paper is based on information from engine manufacturers, airlines, and research studies.

FRETTING IN AIRCRAFT TURBINE ENGINES

by

Robert L. Johnson, Chief, Lubrication Branch and
Robert C. Bill, Materials Engineer, U. S. Army
Air Mobility Research & Development Laboratory
NASA Lewis Research Center
Cleveland, Ohio, U. S. A.

SUMMARY

Fretting is always a nuisance problem and, at times, a critical problem to the manufacturers and operators of aircraft turbine engines in the United States. The most critical fretting problems are on fan, compressor and turbine blade mountings and dampers, on splines, on secondary sealing elements of face-type seals, and to a lesser extent on thrust rings of oil damped rolling element bearing mountings. In addition other components where intolerable fretting may occur include: clamping devices (i. e., disk spacers), static seals, flexible mountings, tubing at clamps, feed throughs, over-running clutches (helicopters), shaft mountings for gears, bearings and other mechanical components as well as combustor slip joints and thrust reverser face and lap joints. Structural fatigue failures can originate at fretting damage.

Secure clamping to prevent relative slip between surface elements is recognized as the one approach to prevent fretting; however, it is not a feasible approach in a lightweight flexible machine like an aircraft turbine engine. The engine designer approach to avoid fretting is usually to harden surfaces, apply solid lubricants and to increase liquid lubricant supply. The field operations approach is to use solid lubricant and metallic or cermet coatings. More consideration should be given to: The adhesion of nascent metals; the maintenance of films, (including oxides) by matching film deformation with substrate metal deformation; the shear properties of the coatings and the properties of oxides (i. e. abrasivity) of surface materials and coatings. Vacuum deposition of coatings by sputtering and ion plating has particular promise as an economic method of depositing adherent thin films to inhibit fretting.

INTRODUCTION

Fretting is a historic problem in all types of rotating machines; it is, however, only one of the many wear problems in aircraft.(1) The fretting problem is seldom considered adequately in the original design of a machine but plays a real part in the development and early service operation. One potential catestrophic result of fretting damage is the adverse effect on the fatigue life of mechanical components; in such circumstance fretting is critical to the dependable operation through the entire service life of the machine. In the case of aircraft turbine engines fretting is always a nuisance problem and too frequently contributes to critical failures. Elucidation of the fretting fatigue mechanism and "anti-fret" techniques for aluminum alloys to 150° C as well as titanium alloys to 500° C have been considered by the AGARD Structures and Materials Panel since 1967.(2)

Aircraft turbine engines are high rotating speed, flexible machines that operate over wide ranges of temperatures, pressures, speeds and external as well as internal stresses. Fretting usually produces both polished and pitted areas; it occurs at all temperatures, at varied low to high slip velocities, and with slip amplitudes even less than 0.03 mm (0.001 inch). Progressive fretting produces galling, resulting in rough torn areas of the surfaces. Many design situations in turbine engines dictate that surfaces in loaded contact must move slightly relative to one another as a result of vibratory and other forces. The trend in advanced engines is toward reduced weight, increased rotative speeds, super critical shafting, higher pressure ratios, higher temperatures, with more carefully sealed systems; each of those items tends to accentuate the seriousness of the fretting problem. Thus, a problem that is now always a nuisance but sometimes causes critical failures in aircraft turbines can only become of increased importance. The long term solution is to be sure the engine designers recognize the fretting problem and for them to use such guidelines as are available to minimize its impact on the machine; further, more understanding and better means of mitigating fretting are needed.

The objective of this paper is to summarize the fretting problems that are commonly found in aircraft turbine engines in the United States. Also, some general discussion is presented on mitigation of fretting in such engines.

This paper was developed on the basis of information made available by maintenance personnel of several airlines in the United States, by representatives of Pratt and Whitney Aircraft, General Electric Company, AVCO-Lycoming Division and Detroit Diesel Allison Division of General Motors; their cooperation is sincerely appreciated. The compilation is purposely generalized to avoid specific identification of engines and manufacturers. Some of the recommendations come from specific studies while others are from general engineering practice.

GENERAL SURVEY AND DISCUSSION OF PROBLEMS

A specific list of fretting problem areas in aircraft turbine engines is as follows:

- Airfoil roots in rotors and stators
- Stator vane and shroud interface and midspan shroud blade dampers
- Splines and rotor assembly stackup interfaces
- Piston ring secondary seals, as for face seals
- Torque pins for seal mountings
- Fasteners including threads, bolted joint surfaces and disconnect rings
- Metal static seals
- Bearing bores, interfaces, raceway keys and thrust dampers
- Variable stator bearings
- Gearbox hanger and other rod end bearings
- Engine mounts and thrust links
- Slip joints for burners and plumbing such as fuel tubing
- Disk spacers
- Planet gear shafts
- Clutches
- Joints and interfaces between, titanium, aluminum and austenitic stainless steel components

The problems all fit into the three widely accepted progressive stages of fretting: (1) the initial adhesion and metal transfer, (2) the production of debris in a reactive (i. e., oxidized) state, and (3) the steady state condition[3] that can be adhesive, abrasive, corrosive and fatigue wear. The geometry of the fretting part and the properties of the debris have much to do with the manner by which the steady state wear condition progresses because of debris retention or removal. As indicated previously, the most catastrophic result of fretting is premature fatigue failure or fracture of components. In the following section several of the problems will be discussed more specifically.

The general engineering approach to fretting takes two distinct paths to solution: While the problem is reduced in many cases by (1) increasing hardness of the surface or by (2) providing increased availability of liquid lubricant, such actions do not get at the basic problem and hence only retard the damage. Since these are generally used approaches, it is clear that they are adequate to avoid catastrophic problems in most circumstances; however, liquid lubricant cannot be provided to many fretting parts.

The only certain approach to eliminate fretting is to prevent relative motion between contacting elements of surfaces. In aircraft turbines where weight considerations prevent rigid structures, it is virtually impossible to prevent relative motions.

Recognizing that the fretting process is initiated by local adjesion provides a fundamental tool in minimizing fretting.[4] Adhesion can be very effectively reduced by solid surface films of either solid lubricants or surface oxides. The influence of solid lubricants and of surface reaction films like oxides for reducing adhesion and fretting is well documented. In engineering practice, films of molybdenum disulfide and graphite have been used for years; to coat or burnish a fretting part with MoS_2 or graphite is often the first approach taken by airline maintenance personnel.

All bolted joints are subjected to some degree of fretting. Examples include the shaft-to-disk interface, the gear carrier-to-frame interface, all threaded surfaces, and many others. Significant reductions in the low cycle fatigue life, particularly for the case of turbine disks, have been attributed to this fretting damage. Such joints have the greatest clamping forces in the engine, hence the least probability of relative motion. The fact that fretting is a problem at these locations illustrates the impracticality of generally reducing fretting by calling for higher clamping forces. In addition, going to higher clamping forces would increase the loading on already highly stressed bolted joints, which are particularly susceptible to fatigue failures. [5]

Mainshaft bearings which are subjected to loads resulting from rotating component unbalance tend to fret at the outer race on the axially clamped surfaces. Gear box bearings fret between the bore of the inner race and the shaft. Chromium plating is reported to reduce the fretting problem. In high speed bearings oil film damping is employed to minimize vibration effects; the floated bearing race is secured from rotation by a series of (e.g., 4) lugs resembling rectangular keys. Those bearing lugs are common candidates for fretting damage.

Over running clutches used in helicopter rotor drive trains introduce significant fretting problems. During engagement of the over running clutch, the inner and outer races of the bearings supporting the rotor shaft rotate at the same speed and the balls vibrate in place. The type of damage observed is illustrated in figure 1 and resembled that called "false brinelling" which was an important problem in wheel bearings of new automobiles transported by rail. Incidentally, the problem of fretting during transport remains of concern for rotating machinery; the aircraft turbofan engine fan roller bearings are most susceptible.

Planet gear shafts which clamp the two supporting roller bearings together with the gear to provide a one piece carrier, fret in the gear bore and to a lesser extent in the bearing bore (fig. 2). The initial fits allow for substantial interference (to 0.03 mm (0.001 in.)) and the SAE 4340 shaft is chromium plated.

Combustor case failures have been attributed to fretting initiated fatigue cracks. The fretting action occurred at the slip joint connection between the compressor discharge tubes and the combustor inlets. In some cases fretting fatigue cracks propagated through a welded seam joining the sections of the combustor. Structural reinforcement was used to minimize the progressive damage but the fretting problem was not eliminated.

Fretting damage to stainless steel fuel tubing has induced fatigue failures by fracture at connector locations where the seal collar contacted the tube. Solutions used usually provide for clamping in attempts to immobilize the tubing.

The use of austenitic steel parts in engines is common and it should be noted that single phase alloys are particularly susceptible to adhesion and hence to fretting with a broad spectrum of contacting materials. There are a multiplicity of similar problems in engines since designers often prefer to use stainless steel because of other virtues. Aluminum and titanium metals are another group of materials favored by designers for use in tubing and similar applications. Those metals are very susceptible to fretting damage if there is any relative contact motion. Data for aluminum, titanium and several other metals given in figure 3 show a correlation between fretting wear and the ratio of oxide hardness to metal hardness. [6] While this correlation must be used with caution because it does not consider other factors known to be important (e.g., oxidation rates, mechanical properties, metal structure, etc.), it can provide one guideline in minimizing fretting. When other considerations dictate the use of such fretting prone materials as stainless steel, aluminum, and titanium in tubing, coatings to inhibit fretting should be used on susceptible areas. The above results on hardness ratios indicate that caution is needed when considering extremely hard ceramic type coatings to inhibit fretting of relatively soft metals; the important factor is likely the mutual deformability of the coating or metal oxide and the substrate metal. Plasticity must be considered part of the fretting mechanism. [6]

Variable position compressor and turbine stators require combination pivot bearings and seals exposed to aerodynamic as well as mechanical vibratory forces and motions. There are very large numbers (over 1000) in some engines and gas leakage can be significant to engine economy while total friction can dictate the necessity for large actuation forces. Most critical, however, is the fretting wear that causes ovalization of pivot bearing, parts and can require them to be replaced in less than the normal maintenance schedule for the engine. Low elastic modulus materials are indicated for such applications but many such materials are too temperature limited to be generally useful. The trend toward variable geometry components in advanced engines is very clear and, therefore, the impact of this problem will be increased.

Spherical rod end bearings are used for flexible mounting of accessories like gearboxes and for mechanical controls. In mounting assemblies vibratory motions and thermal growth excursions are anticipated while in control applications dithering actions of automatic controls as well as vibrations are prime sources of fretting motions. Within their inherent temperature limits, reinforced polymeric liners, solid lubricant fortified greases and solid lubricant films are used on the bearing surfaces.

PRIMARY PROBLEMS

The primary fretting problems in aircraft turbine engines are in (1) seals, (2) splines and (3) blade mountings and dampers. The problem of rolling element bearing mountings previously mentioned may also become more critical with the increased use of oil film dampers coupled with thrust washers (fig. 4). Distress on the thrust washer from fretting and galling are of major concern; however, cavitation damage and possibly field streaming electric potential discharge damage[7] are additional potential sources of surface deterioration that appear similar to fretting. Carbon thrust washers have been used with some success but a stronger material that can take high unit loads without fretting and galling is needed; attempts to use shot-peened titanium did not correct a problem, with fretted parts becoming loose after 3000 hours of operation. On oil damped roller bearings that are not thrust loaded, the retaining lugs to limit motion of the outer race are also subject to fretting damage where there is impact or normal motion between contacting surfaces. For those lugs, the time honored approach of providing direct oil flow reduces fretting damage but does not prevent it.

Seals

Secondary seals on face type and other shaft sealing configurations are critical parts subject to fretting damage. The fretting problem for such secondary seals is commonly with piston rings sealing against the nosepiece carrier assembly (fig. 5). The piston ring allows the carrier assembly to move axially to compensate for thermal growth, axial machine vibrations and transient displacements including runout of the wear ring. Assembly tolerances of engine parts are such that runout of the wear ring of 0.03 mm (0.001+ in.) are common. With such axial displacements at shaft rotational frequencies, critical fretting motions occur. The piston ring must also serve as a damper to facilitate the ability of the nosepiece to follow or remain in nominal contact or at design film thickness. Thus, the surface loads imposed between the ring and the carrier must be of sufficient magnitude for the resulting friction to give needed damping. Those loading forces on the ring are provided by the differential pressure across the seal and by the spring face loading of the ring. The combination of motion and loading are sufficient to cause significant fretting.

Some commercial seal manufacturers report that 50 to 70 percent of the total leakage through face type seals occurs at the secondary seal. Further, with sustained operation the performance of the primary seal interface improved with wear-in to give reduced leakage while the secondary sealing interfaces suffer fretting wear that doubles the fluid leakage.

Specific data documenting the effect of fretting on seal leakage is given in figure 6. Using the lift pad face type seal (fig. 5) the leakage performance is shown over a 200 hour period; at about midway through the test leakage began to increase as a result of fretting damage. With the gas film seal the primary seal interface does not wear significantly and therefore the change in leakage can be attributed to secondary seal. Figure 7 gives the result of post-test static leakage checks (using the assembly from fig. 6) with the worn seal in the operating position, then the assembly was shifted so the ring contacted an unworn surface of the carrier; subsequently a new ring was used in the same positions. It is clear that fretting has damaged the sealing capabilities of both the ring surface and the carrier surface. In this case the ring was Inconel and the carrier surface was coated with aluminum oxide.

Figure 8 shows the relative fretting wear of the Inconel secondary seal material used in the seal test of figure 5. Also, presented is the relative fretting wear for Haynes-188 an alloy which has reduced adhesion for the nascent metal and improved matching of deformation for the oxide and metal as compared with Inconel. These data were obtained with the fretting apparatus of reference 6 and show very significant improvement with the use of Haynes-188. Haynes-188 rings have been used in subsequent seal testing and are less prone to fretting damage than Inconel rings.

Splines

Striking examples of fretting are found in splines on disassembly of engines (fig. 9). The characteristic red oxide for ferrous surfaces provides vivid illustrations of fretting on splines in particular. Significant effort[8] has been directed at the spline problem. The merit of such studies is clear since it has been reported that the failure of a compressor-turbine shaft spline of an older engine resulted in turbine runaway which led to an engine fire and subsequent crash of the aircraft. As a consequence, it is clear that both elements of the fretted splines should be replaced during overhaul.

The power train splines are subject to less misalignment than accessory splines and can be installed tight. That practice of seeking to use tight splines reduces the effectiveness of the additional approach of achieving a good supply of liquid lubricant to splines to inhibit fretting. Where oil can be maintained on spline surfaces fretting is inhibited.

Accessory splines are usually lightly loaded, poorly lubricated, have rather loosely fitted tolerances and are subject to substantial misalignment. A typical spline material is SAE 4140 steel and is used both hardened and in the soft condition; nitriding and other hardening methods do not solve the problem and neither does a subsequent chromium plate. Reduced fretting has been experienced with beryllium copper as the spline material and with solid film lubrication.

A surface treatment of accessory drive splines (e.g., alternator, hydraulic pumps, fuel pumps, etc.,) using a vacuum coating process has been very successful for one short haul airline. That surface treatment provides a 0.25 micrometer (10 microinch) total coating thickness with a base coating of chromium and included 0.18 to 0.20 micrometers (7 to 8 microinches) of gold. That coating extends the wear life in fretting applications by a factor of 5 or more. The gold coating reduces adhesion and does not form oxidative wear debris that usually characterizes and accelerates the fretting process.

There have been substantial advances in the vacuum coating processes of sputtering and ion plating in recent years.[9] Such coatings are ideally suited for inhibiting fretting. The high kinetic energy of the ionized plating material causes it to penetrate surface defects and to form a diffuse or graded interface and consequently giving good coating adhesion.[10] Coatings can be effectively used in such thin films (e.g., 2000 Å) that even precious metals such as gold may be economic. Further, such thin coatings do ot substantially alter normal engineering dimensional tolerances. Thus, the surficial layer can be designed for optimum resistance to fretting without otherwise influencing the engineering design of the part.

Fan, Compressor and Turbine Blades

There are a multiplicity of fretting problems associated with the various rotor and stator blades in turbine engines. It is common practice to use loose blade mountings to minimize vibrational stresses in the blading. Mechanical forces and aerodynamic forces tend to excite vibrational motion at the blade root mounting assembly. Figure 10 is a sketch of a typical rotor blade mounting indicating sources of fretting damage at the root and at the midspan shroud used on some blades for structural and damping purposes. In addition fretting damage is experienced at the stator vane internal shroud interface.

All manufacturers and operators of turbofan engines have found fretting of the blade retention shoulders and the mating rotor material. Many approaches to the problem have been used with varied degrees of success. Bonded molybdenum disulfide and graphite dry film lubricants, copper-indium spray coatings, silver shims, silver coatings and numerous hard coating methods have been used. The blade roots are often shot-peened and coated. Consistent with previous discussion, the most successful approaches seem to be those coatings that deform with and adhere tenaciously to the substrate metal. Shot-peening is thought to improve adherence of coatings as well as provide other benefits. The fretting problem for blade mounting slots in the fan disks is sufficiently severe that repair procedures to restore original geometry in overhaul maintenance are being sought. These parts are commonly made of titanium and aluminum alloys which are very susceptible to fretting.

In the first stages of the compressor the fretting problem is similar to that in fans in regard to temperature levels. The temperature level is a primary factor determining the types of coatings that may be used. Variable geometry compressors utilize stators that can be positioned through a range of positions.

Each blade may have two radial bearings and a thrust bearing as well as a gas sealing interface;

those parts are all exposed to vibration influence of mechanical and aerodynamic forces and motions that give rise to fretting. Additionally the operator linkage and pivots are sources of fretting problems. Low friction materials with low elastic moduli including polymer compositions and mechanical carbons have given useful performance in such parts. With the use of variable geometry features at higher temperature locations the types of pivot materials will have to be changed. Solid lubricant, metal, ceramic composite materials will merit increased consideration. [11]

Figure 10 also illustrates the type of blade mounting surfaces at the rotor blade root interface where critical fretting problems occur. Figure 11 is a photograph of a fretted blade root mounting surface. As mentioned previously, fretting and galling are potentially dangerous in that fatigue cracks propagate from the damaged surfaces. Cracks developed in the rotor have led to failures.

In the turbines, the primary current fretting problem is with the blade retention surfaces in the high pressure stages. Most of the fretting removal of metal is on the rotor disk. The materials and designs are defined by thermal and structural considerations with secondary concern for fretting. Thus, in areas where fretting occurs coatings are used. The temperature levels impose significant limitations on the fretting inhibiting coatings that can be used. Plasma-sprayed coatings of metals with low adhesion and that form oxide films that are tenacious and show lubricating properties have given favorable results. Useful coatings may be hard facing or hexagonal cobalt alloys with either single phase or multi-phase structures and oxides that reduce adhesion. It is anticipated that solid lubricants can be used more effectively in this temperature regime but caution must be exercised in regard to interaction (i. e., grain boundary penetration) that can reduce structural integrity of the disk and blade. Preoxidation of Haynes-188 alloy was found to inhibit fretting and galling of fasteners in cyclic high temperature exposures and similar treatment may be useful with disk and blade alloys.

RECOMMENDED APPROACHES

Identification of the mechanisms involved in fretting wear provides for various rational approaches to reducing the fretting problem. Since it is generally agreed that fretting wear is initiated by adhesion between the contacting surfaces, methods of reducing adhesion stand as potential solutions to the fretting problem.

In general, the best way to reduce adhesion between two surfaces is to separate the surfaces by means of a lubricating film. This is the role that liquid lubrication plays in the case of rolling and sliding element bearings. In a fretting situation, however, it is very difficult to maintain a liquid film in the nearly static regions of contact. In principle, it is necessary to rely on the mobility of the liquid lubricant for replenishment in the contacting areas. Furthermore, in most of the fretting problem locations pointed out, there is no possibility of providing for adequate liquid lubrication. Here other means must be used to reduce the adhesion between the contacting surfaces.

Fundamental studies of adhesion suggest that several new approaches might be applicable to the problem of fretting wear. Experiments with copper-aluminum alloys have demonstrated that thermally induced segregation of aluminum to the alloy surface does occur. [12] The presence of aluminum on the surface in air imparts the adhesion properties of aluminum oxide to the alloy. This line of investigation may lead to the identification or development of alloys that spontaneously generate a self-healing surface film, different in composition from the bulk alloy, with properties of low adhesion and consequently good resistance to the initiation of fretting wear.

Other fundamental adhesion studies[13] have shown that surface crystal structure and crystallographic orientation significantly affect the adhesion properties of alloys. In general it has been observed that hexagonal close packed metals are not so prone to undergoing adhesive wear damage as are cubic metals. It has also been observed that adhesive wear is reduced when the close-packed crystallographic planes are oriented parallel to the contacting surfaces. These studies suggest that techniques may be developed along the lines of varied surface chemical composition and/or thermo-mechanical treatment to provide a low adhesion surface structure for advanced wear resistant alloys.

Further details of these and other adhesion phenomena will be presented in a separate paper. [4]

It has long been realized that the surface oxide films that form naturally on metals can be very effective at reducing wear between contacting metal surfaces. The success of new, high temperature oxidation resistant alloys depends on the spontaneous generation of a thin, tenacious surface oxide film. High temperature service conditions and the development of these new high temperature alloys has stimulated interest in applying this approach to the fretting problem. A preoxidation technique has been successfully used in the case of a high temperature fretting problem encountered in a Haynes-188 fastener assembly; the data of figure 8 for that metal were obtained without the benefit of such preoxidation.

The addition of small quantities of yttrium, yttrium oxide and rare earth metals are thought by some to improve the tenacity of the surface oxides,[14, 15] either through a mechanical "keying" mechanism, a subsurface hardening mechanism via the precipitation of fine oxides in the metal matrix, or through the generation of a more diffuse metal-oxide interface. Whatever the increased tenacity mechanism may be, it is reasonable to suppose that it would afford increased resistance to high temperature fretting in an oxidizing environment. This possibility is currently being investigated for the case of some nickel-chromium alloys.

Various coatings have been applied to surfaces subjected to fretting and have shown some degree of effectiveness. Silver plating has been applied to fan blade and low pressure compressor blade roots with some success. Polymeric coatings, electroless nickel plate and chromium plate have been evaluated for fuel pump spline applications. Some of these coatings work as hard, low wear, protective coatings, while others operate more as sacrificial buffer coatings absorbing much of the vibrational amplitude by themselves deforming.

In the past, the application of coatings containing solid lubricants such as MoS_2 has been encumbered by the need of binder phases and inconvenient curing cycles. The sputtering technique,[9] a relatively new method of surface coating, provides a means of applying a fully dense coating of MoS_2 onto a metal substrate. Such coatings have shown promise in experimental studies. The thinness of these coatings is such that the coating will not interfere with dimensional tolerances, yet sufficient MoS_2 is present to afford lubrication to the fretting interface.

By use of the ion plating technique, thin, wear resistant, strongly adhering lubricant coatings may be applied to a substrate. The high energy of impingement of the coating ions makes this coating technique unique from the standpoint of coating tenacity.

CONCLUDING REMARKS

Current views on fretting in aircraft turbine engines of the United States were solicited from representatives of the engine manufacturers and users. The results are generalized and reported without identification of specific organizations or engines. Generalization was not difficult because the same problems were common. Some unique approaches to mitigation of fretting are characteristic to specific organizations but many of the organizations used very similar mitigation methods.

The critical fretting problems are associated with seals, splines as well as blade mountings and dampers. Fretting occurs also at most clamped interfaces, bearing mountings and dampers, slip joints, threads, and raceway keys or lugs.

Mitigation by solid clamping to prevent slip between surface elements is not always effective in flexible lightweight machines. Liquid lubrication and increased surface hardness are favored by designers to limit fretting. Solid lubricant and metallic or other coatings that reduce solid surface adhesion are useful.

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E-8030

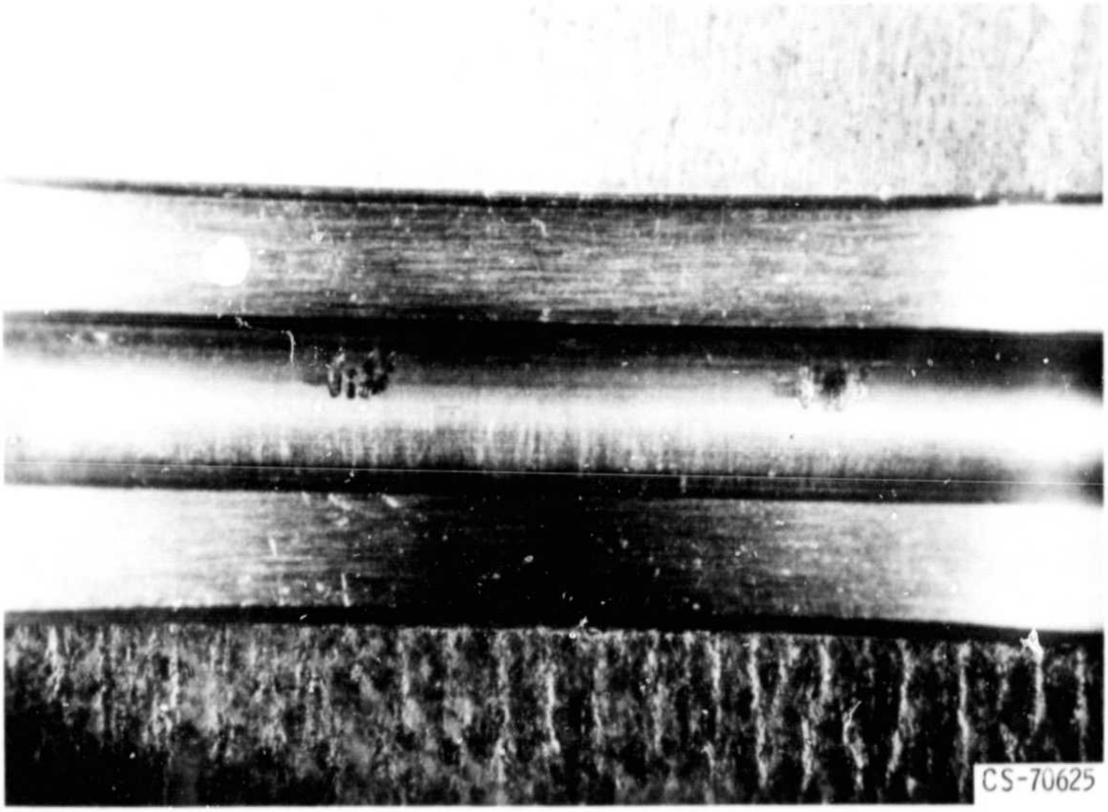

Figure 1. - Fretted area on the outer race (SAE 52100) of an over running clutch bearing from a helicopter drive train.

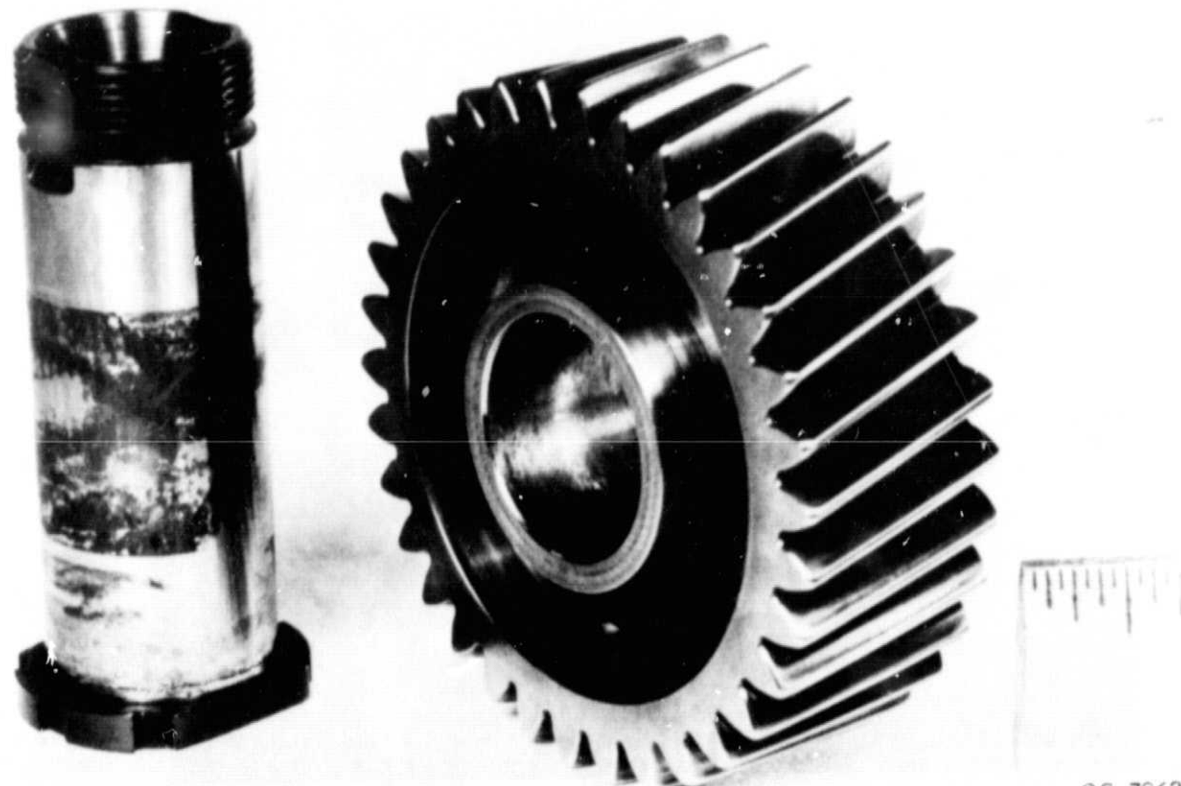

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Figure 2. - Fretting of a planetary gear shaft.

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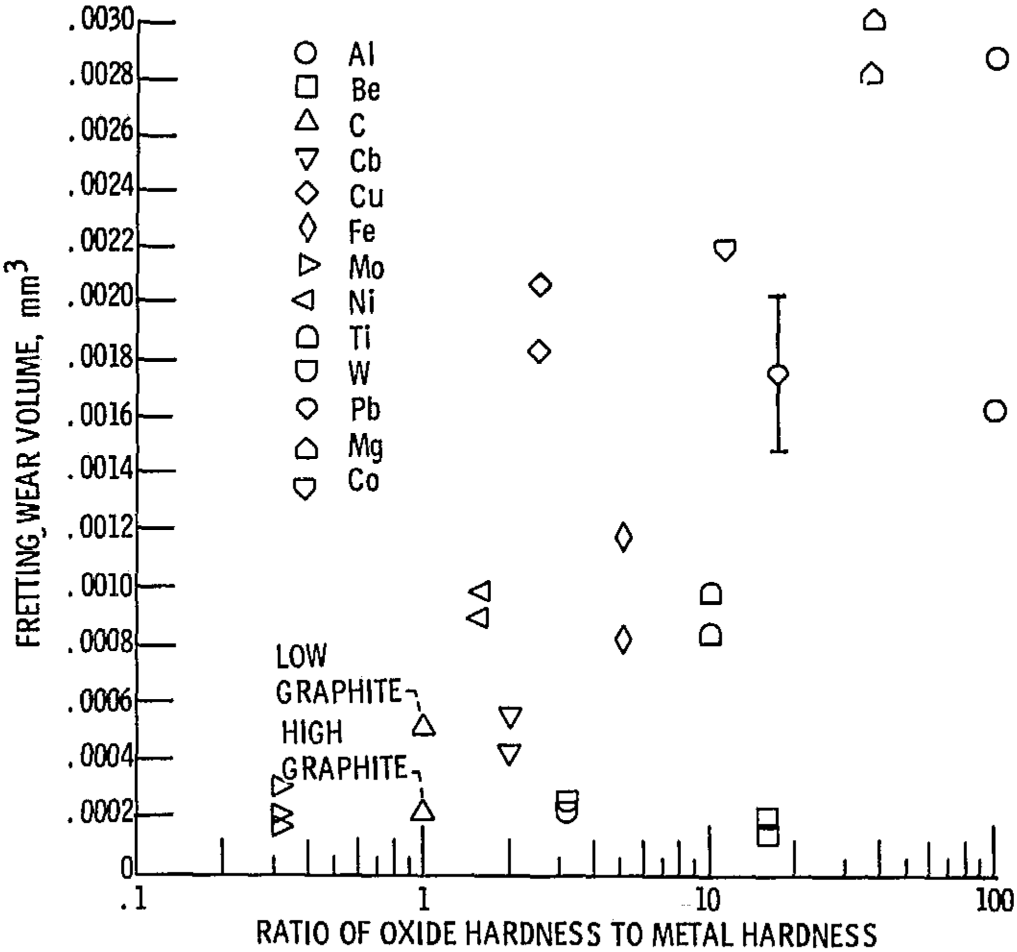

Figure 3. - Fretting wear volume after $6x10^5$ cycles as function of ratio of oxide hardness to metal hardness.

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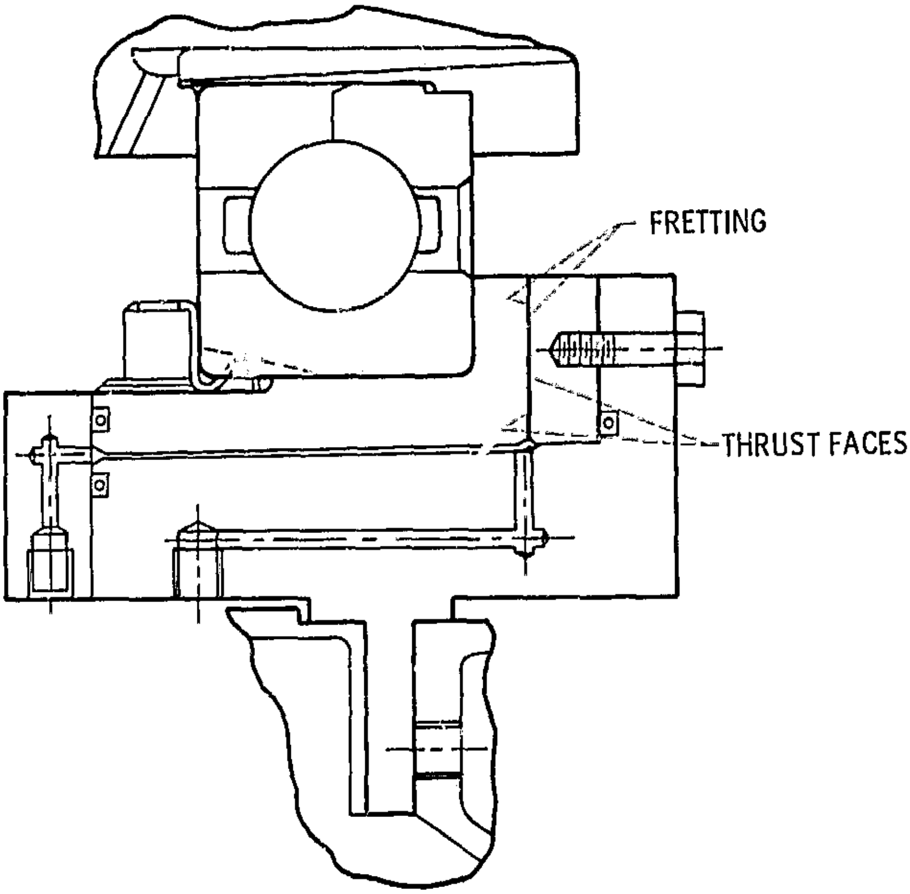

Figure 4. - Fretting of the thrust faces on a damped bearing assembly.

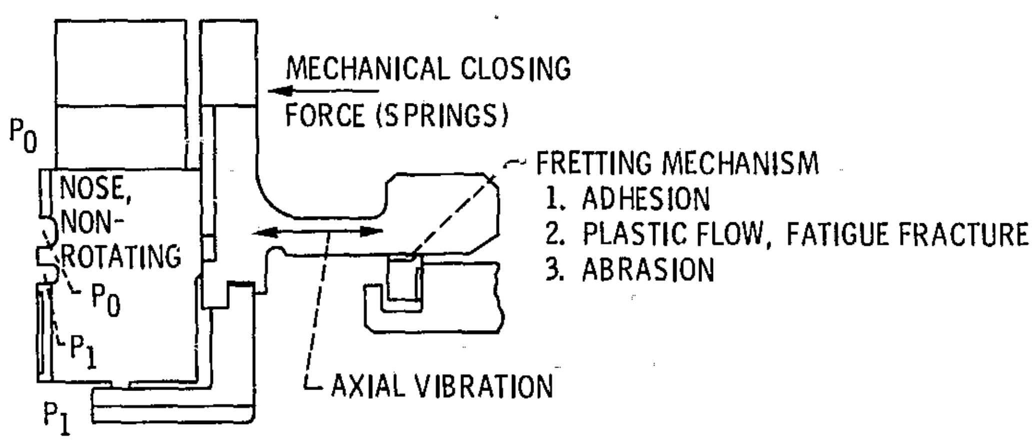

Figure 5. - Face seal fretting problem location.

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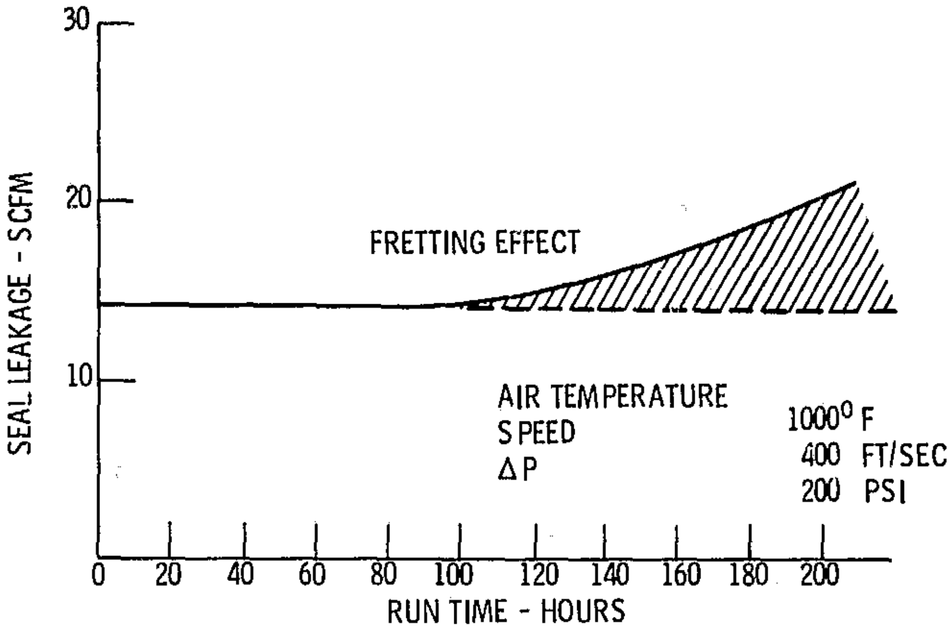

Figure 6. - Gas-film seal leakage during 200 hours of operation.

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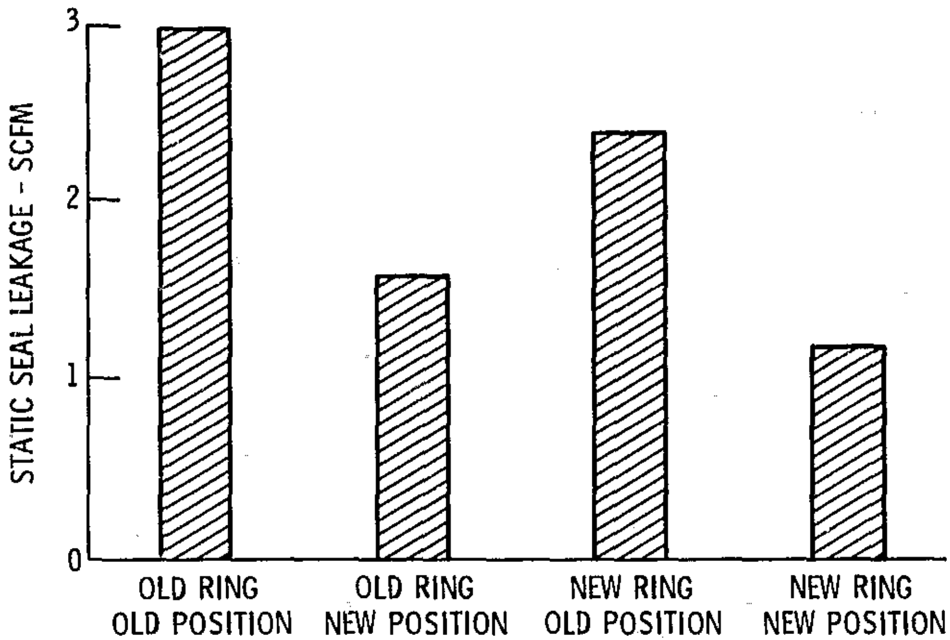

Figure 7. - Effect of fretting of the piston ring and carrier surfaces on leakage at 20 psi ΔP, after 570 hours of operation.

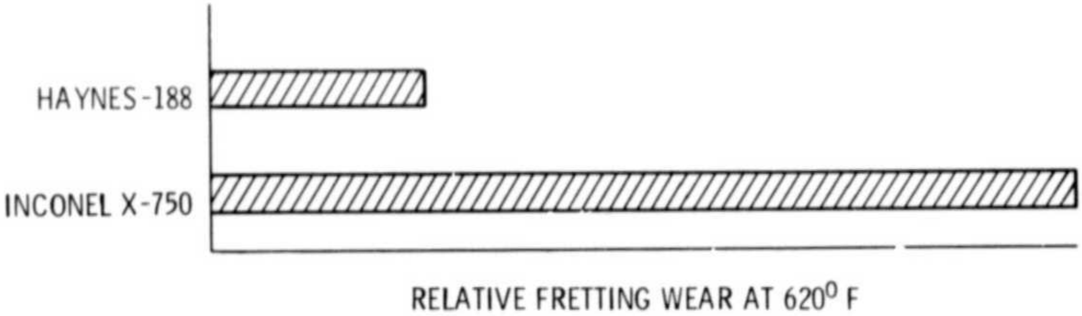

Figure 8. - Fretting wear of two candidate secondary seal materials.

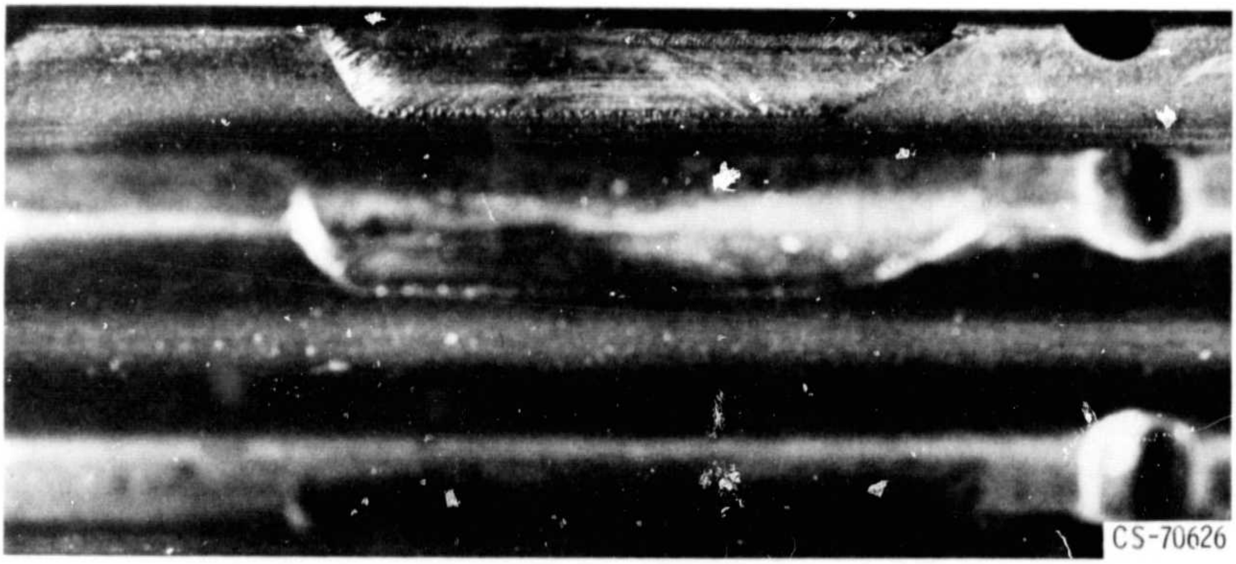

Figure 9. - Fretted spline surface.

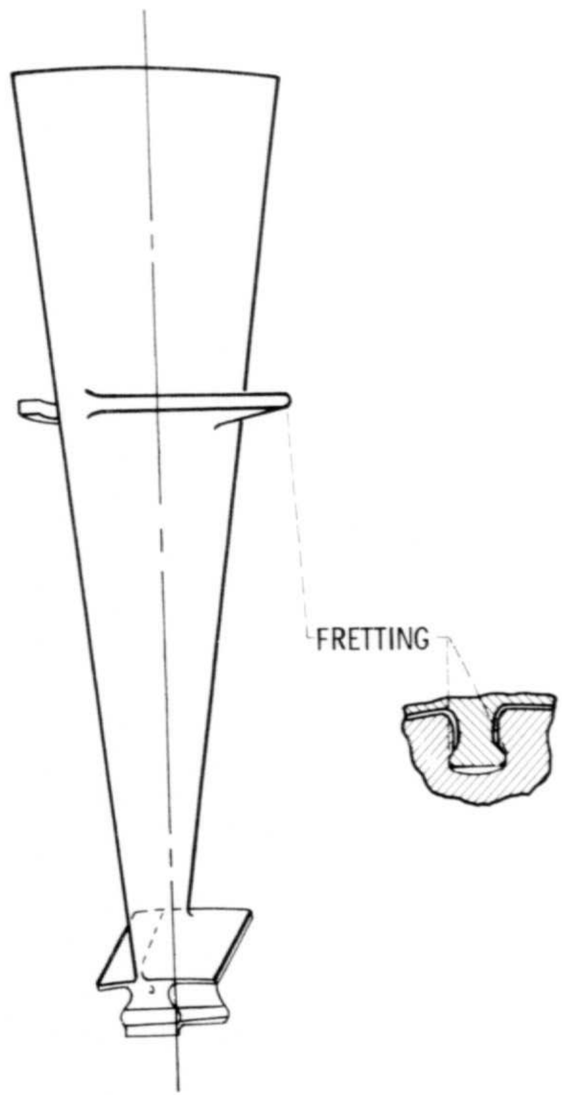

Figure 10. - Compressor blade and blade root detail.

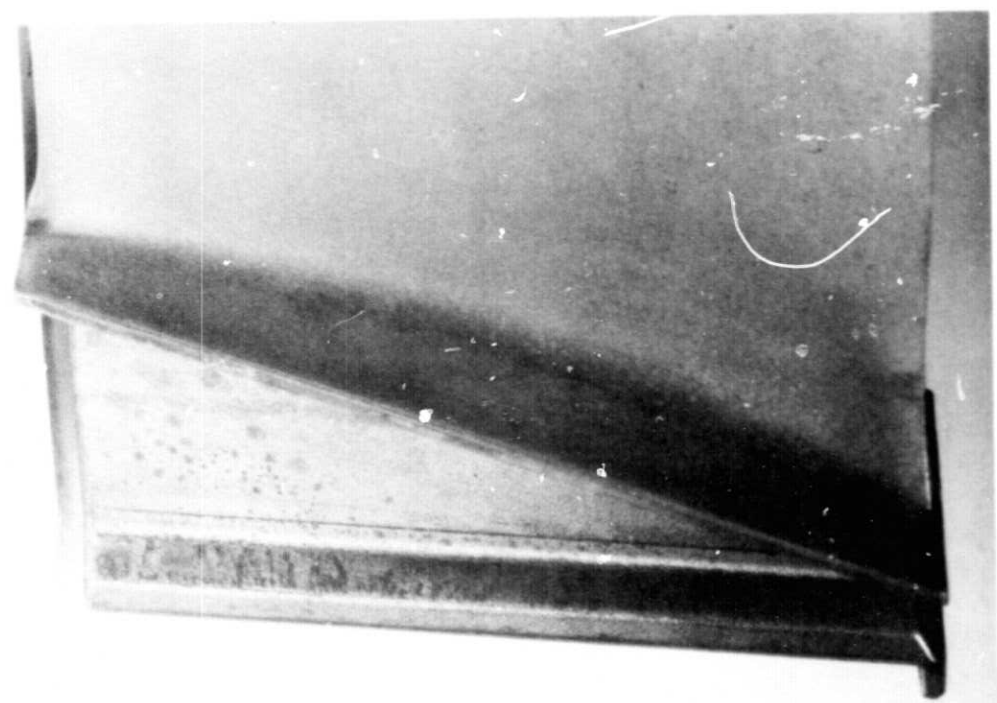

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Figure 11. - Fretting of a compressor blade root surface.