

SAE
AERONAUTICAL INFORMATION
REPORT
NO. 47

FRETTING



December 15, 1956

PREPARED BY
COMMITTEE S-2, HELICOPTERS
SOCIETY OF AUTOMOTIVE ENGINEERS, INC.
485 Lexington Avenue New York, N. Y.

CANCEL



Documents

Document Sharing Hub

Feb. 1992

Section 7C of the SAE Technical Board rules provides that: "All technical reports, including standards approved and practices recommended are advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. There is no agreement to adhere to any SAE standard or recommended practice, and no commitment to conform to or be guided by any technical report. In formulating and approving technical reports, the Board and its Committees will not investigate or consider patents which may apply to the subject matter. Prospective users of the report are responsible for protecting themselves against liability for infringement of patents."

FRETTING

The Subcommittee of SAE Committee S-2 that prepared this report consisted of the following:

H. Hirsch, Chrm. - Hughes Tool Co., Aircraft Division
C. C. Boswell - Hughes Tool Co., Aircraft Division
J. L. Palmer - Hughes Tool Co., Aircraft Division

SOCIETY OF AUTOMOTIVE ENGINEERS, INC.

Committee S-2, Helicopters

Kenneth Gillmore, Chairman
Vertol Aircraft Corp.

Stephen du Pont Doman Helicopters, Inc.	J. P. Perry Eastern Rotorcraft Corp.
F. L. Doblhoff McDonnell Aircraft Corp.	R. H. Prewitt Prewitt Aircraft Co.
J. O. Emmerson Kaman Aircraft	C. E. Schneck Kellett Aircraft Corp.
F. A. Erickson Brantly Helicopter Corp.	C. M. Seibel Cessna Aircraft Co.
L. M. Graham Bell Aircraft Corp.	N. M. Stefano Fairchild Aircraft Div.
Harold Hirsch Hughes Aircraft Co.	M. A. Wachs Sikorsky Aircraft Corp.
R. A. Wagner Hiller Helicopters	

APPROVED BY SAE AERONAUTICS COMMITTEE

C. E. Mines, Chairman
Allison Division - GMC

R. D. Kelly, Vice-Chairman
United Air Lines, Inc.

G. W. Brady Curtiss-Wright Corp.	F. W. Fink Ryan Aeronautical Co.
J. B. Johnson Wright Air Development Center	W. C. Lawrence American Airlines
W. G. Lundquist Wright Aeronautical Division	D. M. McGrath Bendix Aviation Corp.
Arthur Nutt Lycoming Division	C. L. Sadler Sundstrand Aviation Div.

TABLE OF CONTENTS

TECHNICAL DISCUSSION OF FRETTING	
A. INTRODUCTION	1
B. SUMMARY	3
C. HISTORY	5
D. OCCURRENCE	9
E. THEORIES	10
F. DANGERS	12
G. EFFECTS OF VARIATION IN ENVIRONMENTAL PARAMETERS	17
1. Lubrication	17
2. Surface Finish	20
3. Surface Hardness	21
4. The Metal Oxide	23
5. Effect of Various Surface Preparation	24
6. Temperature and Humidity	26
7. Effect of Load	26
H. PREVENTION AND MITIGATION OF FRETTING	28
BIBLIOGRAPHY	30
ABSTRACTS OF IMPORTANT PAPERS	36

FRETTING

A. INTRODUCTION

This report has been prepared in connection with Project No. 55 of the Society of Automotive Engineers Committee S-2 for Helicopters. The project was aimed at the preparation of a report describing the phenomenon commonly called "fretting corrosion"; i.e., its cause, effect, dangers, prevention, etc. In addition, it was hoped that Project 55 could be a continuation of Project 27, which had the object of collecting the scattered data on the subject of fretting corrosion.

The term "fretting corrosion" is the name that is most frequently applied to the type of surface damage that occurs when two surfaces are in contact under load with small relative motion at the contact surface. In the usual case, the motion is alternating and of a vibratory nature. In the most common cases where this phenomenon occurs between surfaces one or both of which contains iron, red iron oxide is formed at the contact surfaces. This oxidation or corrosion product led one of the earliest researchers on the phenomenon, G. A. Tomlinson, to coin the name "fretting corrosion". Since that time the phenomenon has been referred to by many other names, some of which are:

Friction Oxidation	Seizing
False Brinelling	Chafing
Wear Oxidation	Chafing Fatigue
Surface Fatigue	Galling
Frettage	Galling Fatigue
Cocoa	Bleeding

Some of these names are interchangeable with the term "fretting corrosion", while others, such as Surface Fatigue, Seizing, and Galling, refer to other phenomena that are sometimes mistaken for fretting corrosion.

More recent experiments have shown that fretting "corrosion" also occurs when the relative motion takes place in an inert atmosphere or the surfaces are of an inert material, such as ruby, quartz, or glass. Therefore, the tendency has been to shorten the name of this phenomenon to "fretting". Since fretting only occurs when the contact surfaces have relative motion, and results in surface damage as a result of mechanical action, it may be classified under the broader heading of wear. The definitions of fretting and fretting corrosion as proposed by W. E. Campbell (Reference 50) will be used in this report:

Fretting - Wear caused by oscillatory slip of small amplitude between two surfaces. The amplitude below which wear is to be considered fretting will be that which is large enough to maintain a lubricant film of finite thickness between the surfaces at all times.

Fretting Corrosion - Corrosion resulting from fretting.

The subject of fretting as defined above can be further divided into cases or types in accordance with the type of mechanism by which it occurs. The first two classifications are the same as proposed by W. E. Campbell (Reference 50).

Class 1 - Fretting that occurs in parts of a mechanism that were never intended to have relative motion.

Class 2 - Fretting that occurs in parts of a mechanism intended to undergo relative motion some or all of the time, but not through the action of anti-friction bearings.

Class 3 - Fretting that occurs in anti-friction bearings.

The purpose of this report is to summarize the present knowledge regarding fretting. In order to do this, the following sections of the report will adhere to the outline presented below:

1. History of fretting, and of research work aimed at defining and mitigating the problem of fretting.
2. Discussion of the occurrence of fretting, with emphasis on how and where it occurs.
3. A discussion of the theories used to describe the fretting phenomenon.
4. An enumeration of the dangers that may accompany fretting.
5. A discussion of the effects of a variation in environmental parameters (including lubrication) on fretting.
6. A general discussion on the means of mitigating or preventing fretting.
7. A bibliography.
8. Abstracts of a few of the more important technical reports on fretting.

Reference numbers appearing throughout the text refer to the papers listed in the Bibliography.

B. SUMMARY

"Fretting corrosion" is the term most often applied to surface damage resulting from small oscillatory motions between two parts. A great number of other terms have been used to describe this process, such as friction oxidation, false brinelling, wear oxidation, etc.; however, since oxidation or corrosion does not appear to be the basic cause of the phenomenon, the present tendency has been to shorten its name to just "Fretting".

Fretting is considered to be a form of wear and is defined as the surface damage resulting from oscillatory surface slip at such low amplitudes that a lubricant film of finite thickness cannot be maintained between the surfaces.

Fretting can and often does occur between surfaces that were never intended to experience relative motion, such as splines, keyways, fitted members on rotating shafts, shrink and pressed fits, under clamps, and in riveted or bolted joints.

Fretting is more common at surfaces that are designed to undergo relative motion and experience periods of small amplitude oscillations, or periods of supposedly no motion in mechanisms subject to vibration: i.e., ball, roller and needle bearings in oscillatory service, universal joints, wrist pins, propeller bearings, aircraft control system bearings, leaf springs, etc.

There is some controversy concerning the mechanisms of fretting, and several theories have been proposed and are under investigation: however, in each case, small particles of the surface material are loosened and appear in the contact area. When these particles become trapped in the contact area they form an abrasive that accelerates fretting wear. In cases where oxygen is present and the material will oxidize at the temperatures present, the small particles oxidize readily. If the oxides produced are very hard, as in the case of iron or aluminum, the trapped oxide particles are highly abrasive and the contact area becomes an area of highly concentrated intense wear.

Fretting can be stopped only by eliminating the slip at the contact surface, or by establishing a continuous lubricant film. In general, increasing the amplitude of oscillation or a reduction in load will help maintain a lubricant film. The surface slip at contact surfaces can sometimes be eliminated by increasing the load or pressure until the surface friction is so great that the motions are absorbed by elastic deformation of the mating parts. In the case of small displacements or misalignment, a flexural pivot will provide a better installation from a fretting standpoint than plain or anti-friction bearings.

In the more general case wherein fretting cannot be eliminated, the damage can be reduced and the life of the parts prolonged by proper consideration of the following experimental results:

- a. Very fine finishes appear to have a greater tendency to fret.
- b. Increased hardness of steel specimens show a beneficial effect unless stainless steel is one of the materials.
- c. Surfaces of unlike finish and hardness appear to have less tendency to fret.

Chemically clean surfaces show a great tendency to fret. Surface films and surface oxides have a tendency to reduce friction, wear and fretting. The addition of a lubricant in the contact surface will further delay the start of fretting. The use of a rough surface with lubrication appears to be of great benefit. In connection with anti-friction bearings, a low viscosity, semi-fluid lubricant is desirable.

C. HISTORY

Fretting has been occurring in mechanical machinery for a great many years. As the stress level, hardness, accuracy, surface finish, and life requirements on mechanical parts have steadily increased in recent years, fretting has become more and more a problem. The first reference to the phenomenon in the literature is a paper by Eden, Rose, and Cunningham (Reference 1) published in 1911. The authors reported that while conducting fatigue tests, they were troubled by a red iron oxide formation in the grips of their specimen holders. They concluded that this corrosion was due to a varying stress level at the contact surfaces, and that it was similar to the rust found between a wheel and its axle, or between a key and keyway.

The next report of importance did not occur until 1927 when G. A. Tomlinson (Reference 2) reported the first experiments concerned directly with the phenomenon of fretting. Tomlinson was, in fact, the first individual to coin the term "fretting corrosion".

As a result of his experiments, Tomlinson proposed his well known "molecular attraction" theory. Although this theory is not generally supported today, many of the conclusions drawn from these experiments are of such importance that they will be briefly discussed below.

1. It was observed that chemically clean surfaces fretted at much lower contact stresses than surfaces mechanically cleaned by wiping. From these tests it was concluded that surface films form protective coatings that delay fretting. In support of this conclusion, it was observed that when the surfaces were lubricated with vaseline or castor oil, either fretting was delayed, or higher stresses were permissible. Further tests on lubricated specimens showed that the contact stresses at which the coefficient of friction increased (oil film breakdown) were the same as the contact stresses at which fretting occurred.
2. Static tests under very high loads failed to produce fretting, even after allowing the load to remain in place as long as forty hours. This proved that mechanical action was required, and that the phenomenon could not be due to electrolysis or chemical action.
3. No fretting could be produced when pure rolling motion was introduced between the contacting bodies, thus indicating that mechanical slip is required.
4. Heat generation calculations indicated that heat is not a factor in producing fretting.

In 1930 Max Fink (Reference 3) conducted a series of experiments concerning unidirectional wear. Although the author was not concerned with fretting, his work has often been referenced in this connection. The tests were conducted on flat disks in contact at their circumference and rolling with one percent slip. The tests showed a greater amount of wear and greater friction in air than in nitrogen. A film was formed on the surfaces tested in air that was assumed to be made up of iron oxide FeO . From these observations the author concluded that wear produces oxide films that grow thicker and thicker until they break up. The oxygen (air) trapped in the low spots is greatly compressed by deformation of the higher peaks in contact and the high pressures cause the iron and oxygen to combine to form iron oxide FeO . The author concluded that the presence of oxygen created an additional component of normal wear. The author called this additional component of wear "wear oxidation", a term that he changed in later works to "Friction Oxidation".

In a paper published in England in May 1931, Stott (Reference 4) gives the results of an investigation of the wear of instrument and meter pivots. When steel pivots were rotated in contact with sapphire jewels, in the absence of lubrication, fretting occurred with large deposits of fretting corrosion debris. Again no rust appeared under static conditions and it was assumed that motion was required to produce the corrosion. In 360,000 revolutions the friction increased by a factor of from 10 to over 100 times and both steel pivot and sapphire jewels were damaged. Lubrication delayed the damage and greatly increased the life of the bearing.

In 1935 S. J. Rosenberg and L. Jordan (Reference 5) undertook to repeat and extend Fink's experiments (Reference 3). Disks were run in air, nitrogen, and hydrogen with one percent slip and no significant difference in the weight loss of the disks was found. Fink's theory that the presence of oxygen increased wear could not be substantiated.

The tests were continued with the slip increased to 10 percent and using eutectoid carbon steel tempered at 260°C . Specimens tested in air, nitrogen and hydrogen gave approximately the same results, with slightly less wear in hydrogen and nitrogen. Films of what appeared to be iron oxide were formed in all three gases. The authors observed that oxidation in hydrogen and nitrogen could be due to oxygen absorbed in the metals or trapped in the test cell.

An additional series of experiments was performed using steels of varying hardnesses and carbon content, and testing in air, and in hydrogen and nitrogen atmospheres. These tests showed varying wear rates, depending on the specific test conditions, and are summarized in the abstract on this paper (see page 50).

Perhaps the most publicized early example of fretting in the

literature is discussed by Almen in his paper (Reference 6) in 1937. This is the case of damage to automobile wheel bearings that occurred during the shipment of automobiles by railway freight car. To support this investigation, Almen built a test machine capable of oscillating ball bearings through small angles while under load. Tests were conducted under various loads, and with a number of different lubricants. It was concluded that the so-called "false brinelling" of the wheel bearings was not brinelling in the true sense, but rather that the phenomenon was a form of wear which was dependent on, or aggravated by, the presence of oxygen. Furthermore, Almen showed that the wear could be significantly reduced by the use of a low viscosity lubricant.

Experiments by Tomlinson, Thorpe, and Gough in 1939 (Reference 13) confirmed earlier experimentors' conclusions that fretting is due to mechanical slip at the contact surface. New contributions to the knowledge regarding fretting provided by this paper were: (a) the damage due to fretting was greater for highly polished surfaces and for close fits, and (b) the damage appeared to be essentially the same throughout the test load range (the original load was increased by almost nine times during the final tests).

Recognition of the fretting problem in anti-friction bearings appears in several publications by members of the Engineering Staff of the Fafnir Bearing Company (References 32, 33, 34, and 40). Fafnir, in 1947, recommended a reduction in ball bearing capacity to 35 percent of the normal (fatigue) values to allow for the detrimental effects of fretting in installations where oscillating motion occurred. Fafnir also emphasized the importance of proper lubrication in these installations.

Sakmann and Rightmire in 1948 (Reference 38) presented test data that showed that the hardness of the oxides appears to be an important property in connection with fretting corrosion, and that fretting belongs to a group of wear problems for which surface oxidation affords no protection.

During the past five years, many important contributions to the knowledge regarding fretting have been made. Godfrey, at the NACA (See References 39, 44, 56, and 64) has made an intensive study of the problem, including the mechanisms of failure, and the peculiarities of the phenomenon. Rahm (Reference 45) at WADC has studied that effects of various lubricants and bearing race surface finishes the alleviate the problem. The ASTM, in 1952, sponsored a Symposium On Fretting Corrosion (References 49, 50, 51, 52, 53, and 54). Papers presented at this symposium discussed the current status of fretting corrosion, the effects of various lubricants and various combinations of different metals, the effect of fretting on the fatigue resistance of structural components, and testing procedures for measuring fretting corrosion

quantitatively under precisely defined conditions.

Mentioned above are but a small part of the numerous contributions to the study of fretting. Although the Bibliography to this paper indicates an intensification of research on the subject in the last few years, there still remains some controversy concerning the exact mechanism by which fretting occurs, and much work remains to be done in order that the practicing engineer may gain a clear understanding of the causes and cures of the phenomenon.

D. OCCURRENCE

As mentioned in the introduction, Class 1 Fretting is fretting that occurs in parts of a mechanism that were never intended to have relative motion. The earliest reference to this specific problem appears in Reference 1, when the red iron oxide appearing in the grips of a fatigue test machine was compared to rust that had been observed between a wheel and its axle, and between a key and keyway. Other examples where fretting commonly occurs are:

1. Splines
2. Riveted and bolted joints under varying axial loads.
3. Clamped, shrink, and press fitted members under repeated loadings.

Relative motion is not intended to occur between the two mating components in the examples above. However, the amount of motion required to produce fretting (of the order of 10^{-6} inches) can and does occur in these examples, and therefore fretting is commonly present.

A case in point is cited by Fisher (Reference 73). In this example a load variation caused fretting to occur between a steel bolt and a simple lug. Result of the action was catastrophic failure of the lug at loads less than half of those that would normally cause fatigue failure. This type of lug failure is much more common than usually supposed.

A good example of Class 2 Fretting is the case of a leaf spring. Two other typical examples are gear teeth, and torque transmitting slip joints. A relatively large amount of motion occurs, and fretting is commonly present.

Examples of Class 3 Fretting are listed below:

1. Aircraft control system pulley and hinge bearings.
2. Universal joint bearings.
3. Propeller blade retention bearings.
4. Helicopter control system and blade retention bearings.

All anti-friction bearings mentioned above are subjected to small angle oscillation, and therefore fretting. Reference 40 indicates the severe reduction in small angle-oscillating ball bearing load capacity due to fretting found by F. G. Patterson at the Fafnir Bearing Company. The reductions in bearing capacity recommended in this reference are to allow for these detrimental effects.

E. THEORIES

The fact that fretting is a form of the vastly complicated process of wear indicates that it is not a simple problem with a simple solution. Although the phenomenon has been observed and recognized for many years, it is today not completely understood. Despite the extensive research conducted on fretting in recent years, controversy still exists regarding the exact mechanism by which it occurs, and many statements concerning it may be either true or false, depending on the implications. The purpose of this section of the paper is to present the two current theories, and to discuss their applicability.

1. Molecular Attraction Theory - This theory, proposed by Tomlinson (Reference 2) in 1927, is the first of two principal theories of fretting. This theory holds that fretting is a form of molecular attrition (or transfer) caused when alternating close approach and subsequent separation of the molecules of the two mating surfaces occurs. On close approach, the fields of force of the molecules overlap, and on separation the molecules are torn out of both surfaces as a result of breaking the cohesional bonds. Support for this theory is furnished by Savage (Reference 67). He finds that wear debris from carbon rubbing on metals in a high vacuum has acquired extraordinarily high chemical adsorptive activity, indicating that carbon to carbon molecular bonds are broken during wear. This theory is also supported by microscopic observations of Godfrey, and seems general enough to account for various classes of materials.
2. Weld-Breaking Theory - This theory, supported by voluminous evidence, is currently the most popular theory used to explain the phenomenon of fretting. The theory is based on the modern concepts of friction, and holds that (Reference 50), "When two solids come in contact, the force bringing them together is concentrated on a small number of high points in both surfaces. These high points flow plastically under the load, and cold-weld, equilibrium being finally reached when the cross-sectional area of the welded junctions is sufficiently large to support the load. Friction and wear result from breaking of the welds and from plowing of the asperities of one material through the other, the weld-breaking process being the dominant one for most practical purposes". There appears to be a great deal of evidence available to support this theory and, in fact, the theory is not inconsistent with experiments cited in favor of the Molecular Attraction Theory.

The interlocking theory of Feng and Rightmire (Reference 63), is a modification of the weld-breaking theory, and is attractive in that welding is not necessary for fretting wear of metals. However, the theory explains metal transfer

by welding granting that sufficient heat is liberated by the breaking-out action to cause welding.

It is believed that the theory of Uhlig (Reference 78, 80) best explains the phenomenon of fretting corrosion of steel, as Uhlig presents evidence that there is both a chemical and physical factor operable in this connection.

The oxidation that generally accompanies fretting in air can be explained in two ways. The first explanation has already been given in the discussion of Fink's paper (Reference 3). With this theory, the oxidation is the primary reaction and fretting proceeds by removal and reformation of the primary oxide film. A deficiency of this theory is shown in that if oxidation were the primary cause of fretting, elimination of the oxygen in the surrounding atmosphere would stop fretting completely. Attempts to accomplish this have so far met with failure.

A more generally accepted explanation of the manner in which corrosion occurs holds that the virgin surfaces of the metal created when slip takes place combine immediately with oxygen at room temperature. It is well known that exposure of clean metals to air or oxygen results in an immediate reaction which proceeds according to a logarithmic law. Feng (Reference 62) believes that the debris particles are not usually oxidized "instantly", and that those that are in contact with the surfaces of the parts (and that produce the abrasive effect) are distributed among other metallic particles that are in partially oxidized and fully oxidized states.

F. DANGERS

There are two primary dangers that occur due to fretting. These two dangers are discussed below:

1. Destruction of Bearing Surfaces

The primary manifestation of fretting is the progressive destruction of the contacting bearing surfaces. This destruction is generally accompanied by the formation of debris, and a loss of dimensional accuracy.

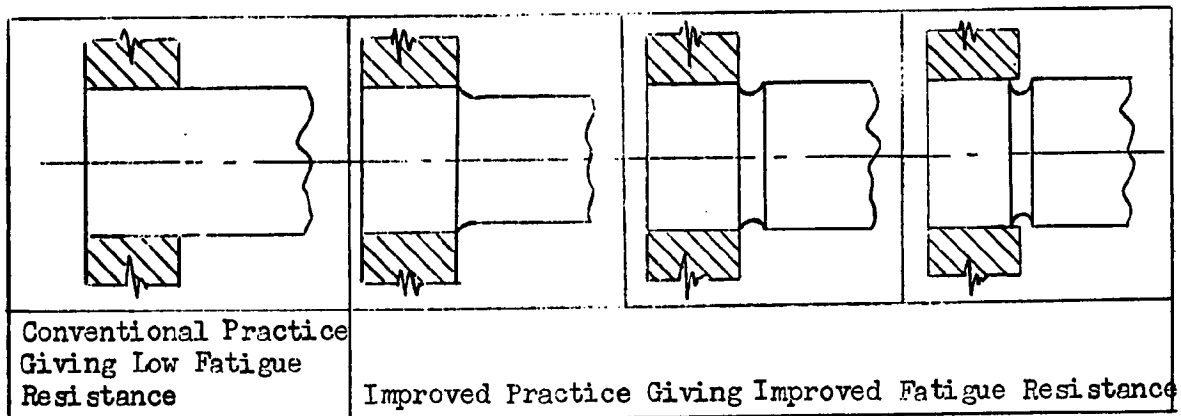
In devices that are intended to undergo relative motion, such as leaf springs and torque-transmitting slip joints, the surface destruction is accompanied by a rapid increase in friction. This friction may increase to the point where it interferes with the normal operation of the mechanism, and, if allowed to continue, may precipitate seizing or jamming, and eventually lead to static failure of component parts of the devices. Progressive failures of this type interfere with the normal operation of anti-friction bearings subjected to small angle oscillatory motion, and are a cause of great concern in helicopter control systems and rotor head assemblies where normal bearing operations are essential. The damage due to fretting in this latter case leads to a much shorter bearing life than would normally be predicted. Bearing failures of this type also may result in misalignment of components, and excessive vibration. Fretting is generally recognized as the most deleterious condition experienced in anti-friction bearings used in modern aircraft.

2. Increased Susceptibility to Fatigue Failure

There are numerous indications that fretting appreciably increases the susceptibility of structural components to fatigue failure. L. E. Bensen (Reference 15) in 1940 presented photographs of some examples where fatigue cracks originated in areas that had been damaged by fretting corrosion. G. Sachs in 1939 (Reference 17) gives examples of propeller blades failed by fatigue where the fatigue cracks originated in the pits caused by erosion of a magnesium blade rubbing against a steel hub. In 1941, G. Sachs and P. Stefan (Reference 19) discussed the "chafing fatigue strength" of some metals. They concluded that the fretting may act in a manner similar to notches and section changes, or similar to corrosion, depending on the metal used, and that fretting causes a severe reduction of the fatigue strength.

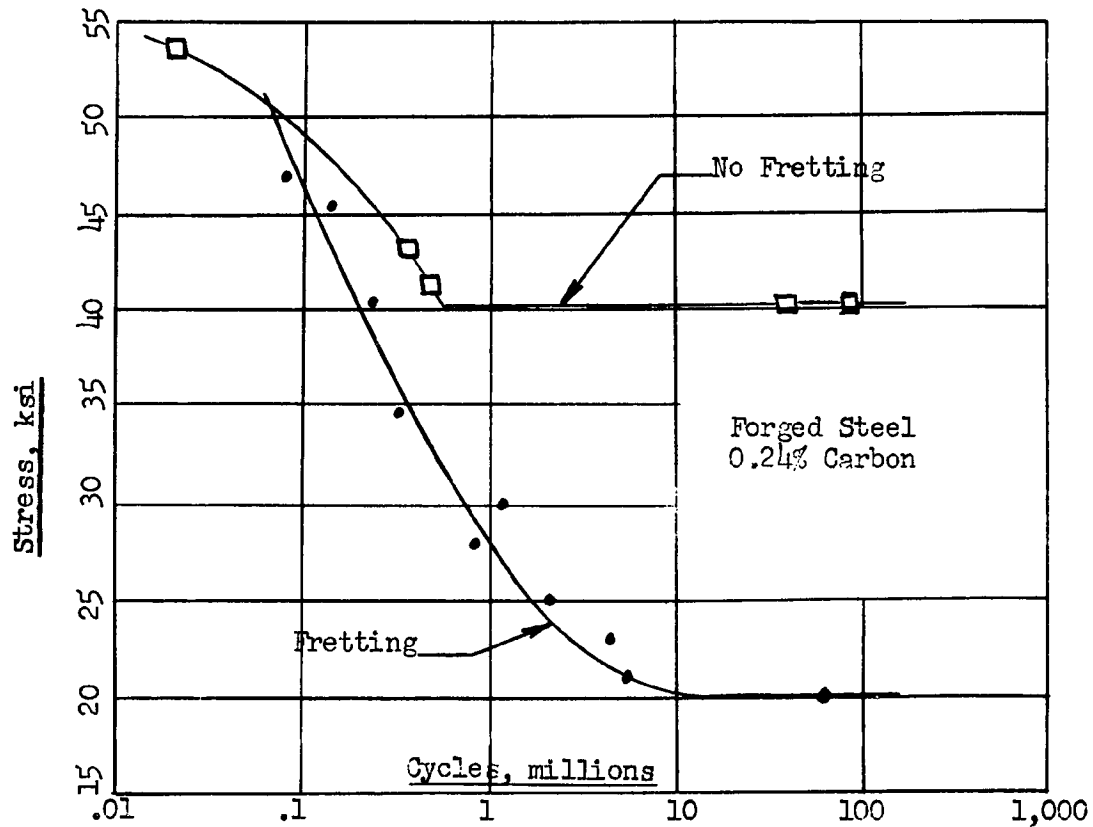
Bennett and Quick (Reference 75) present photographs of an aircraft engine crankshaft that fractured after 220 hours of service. The fatigue crack originated in an area where fretting had occurred under the propeller hub. They state, "In this case the (fretting) pits concentrated the stress to such an extent that the peak stress was greater than the fatigue strength of the steel". This failure is also discussed in Reference 76.

Reference 70 states "The analogy between fretting fatigue and notch fatigue has been confirmed by photoelastic studies of the contacting parts. These show that the stress distribution in a loaded press-fitted part is nearly the same as that in a single piece of the same over-all shape. This explains why the fatigue strength of press-fitted parts can be raised by stress-relieving measures similar to those applied to notch (filleted) parts." Horger (Reference 52) cites examples of improved fatigue resistance in "raised seat" design, as shown below:

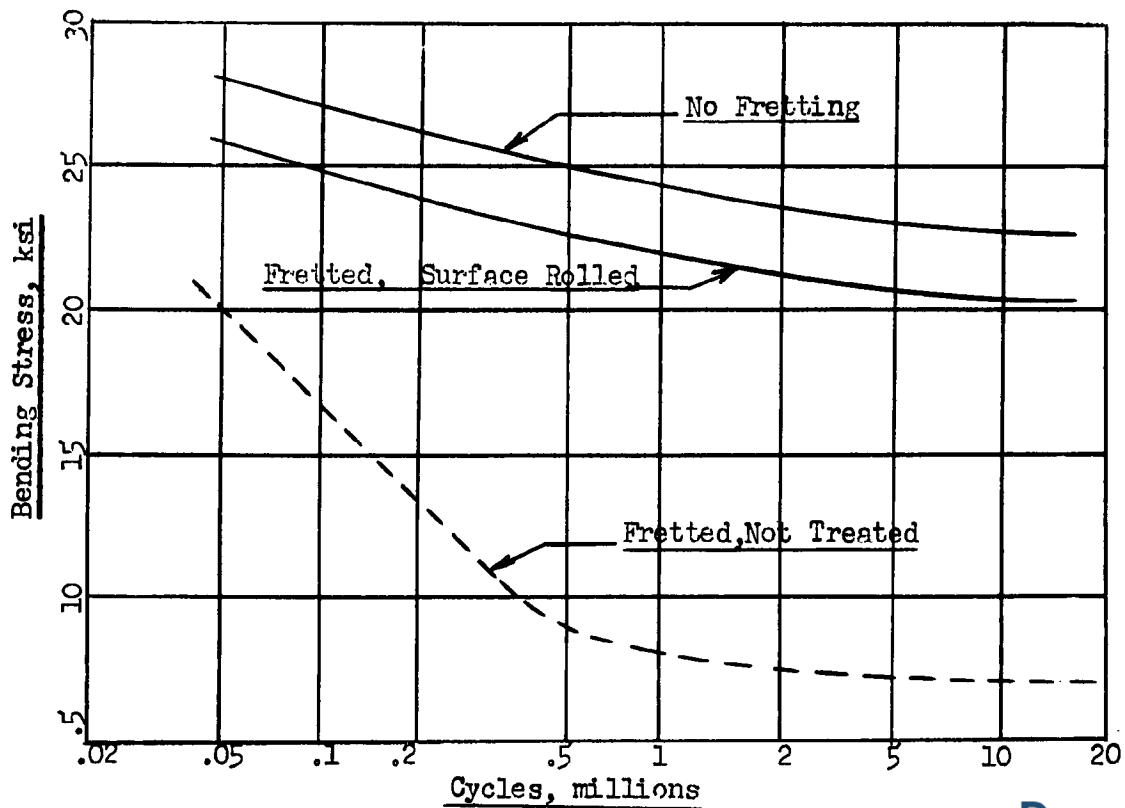


Reference 77 also treats this subject, and presents curves of fatigue stress concentration factors for shafts with press-fitted collars subjected to bending loads.

E. J. Warlow-Davies (Reference 21) conducted a series of experiments designed to determine quantitatively the reduction in fatigue strength due to fretting. The results of the tests show a definite loss of fatigue strength, but due to the limited number of specimens and the scatter, no definite quantitative conclusions could be reached. Of interest, however, is the reproduction of the following graph taken from this reference, showing the S-N curves for tests on similar forged steel specimens with and without fretting.



A similar example by Sachs (Reference 24) is shown below. In this case, surface rolling has been employed to improve the fatigue characteristics of a part subject to fretting. The curves are for surface-rolled and untreated specimens of magnesium alloys:



It is emphasized that the quantitative improvement shown depends, not only on the specific material involved, but also on the roll size and rolling pressure in rolling, or the shot size and pressure in shot blasting. Therefore, the examples are cited only to indicate trends, and not to provide specific design information.

O. J. Horger in Reference 52 correlates and summarizes his work over a fifteen year period on a study of the influence of fretting corrosion on the fatigue strength of fitted members. He states the "fretting phenomenon is responsible for fatigue cracks initiating at stresses below the level at which failure would occur from only the shape effect," and cites 5,000 psi (on steel shafts pressed into sockets) as a typical value. The paper summarizes the following factors with reference to the phenomenon:

- a. The fatigue strength of a shaft pressed into a socket decreases with increasing press-fit pressure to a point where a minimum strength is reached, and then remains constant. The press-fit pressures associated with this minimum strength are generally less than those required to transmit torque or bending moment.
- b. "An improvement may be made in the resistance to crack initiation, but the increase is somewhat limited. Both shape and favorable residual stresses offer the best means for improvement." However, when very long life is required, the designer may find it almost impossible to prevent crack initiation, since the extremely low cyclic stress levels required would result in an impractical design.
- c. "If the environment producing fretting or corrosion is removed, once the crack has initiated after a large number of cycles of very low stress, then the cracks will show little, if any, propagation at the same stress required to start the crack."

Sachs (Reference 72) reports that the damaging effect of fretting is highly dependent on the material, and that fretting-fatigue strength for high strength alloys is independent of the regular fatigue strength or the tensile strength of the material. He further states that "no true fretting-fatigue limits exist."

Sachs states (Reference 70) that for certain specific groups of materials, such as aluminum alloys, the fretting-fatigue strength has been found to be equal to the regular fatigue strength, if this value was very low, as is the case in fabricated aluminum

alloy structures. However, as indicated by the preceding graph, Sachs' conclusion does not appear to hold for magnesium.

Sachs also states that there is a slight dependence upon the structural condition of the alloy. Cast alloys are apparently more resistant than annealed alloys, which in turn are more resistant than either cold-worked or heat-treated alloys, on the basis of equal strength.

Corten, Reference 82, includes some data on the influence of clamping pressure on fretting fatigue strength.

H. Velkoff, Reference 79, cites examples of U.S.A.F. experience in the development of metal helicopter rotor blades. It is pointed out that one of the most critical areas from a fatigue standpoint is the area of blade root retention. On the basis of many fatigue tests that have been conducted on root retention joints, Velkoff concludes that "for typical aluminum blades the maximum allowable alternating stress (10^7 cycles) is approximately 3000 psi when little or no fretting is encountered. In cases where fretting is encountered in the presence of a joint of high stress concentration a maximum stress as low as 1200 psi may be expected. In a well designed joint with severe fretting 1500 psi could be expected."

A few of the more important conclusions concerning reduction in fatigue capacity due to fretting are summarized above. There appears to be no doubt that fretting will lower the fatigue strength of a part; however, there appears to be practically no reliable data indicating quantitatively the amount of such a reduction except that presented by Horger (Reference 52), and Corten (Reference 82). This is, of course, an extremely difficult factor to assess, since there appears to be no convenient method of measuring the severity of fretting on a specific part removed from service.

G. EFFECTS OF VARIATION IN ENVIRONMENTAL PARAMETERS

1. Lubrication

Rahm and Wurster (Reference 45) discuss the effects of various lubricants on the fretting of anti-friction bearings subjected to oscillating motion. The results of these tests indicate that AN-G-25 (MIL-G-3278 Lithium Soap Base) grease, AN-G-15 (MIL-G-7711 General Purpose) grease, and AN-O-8 oil had lubricating characteristics that produced greater resistance to fretting than any other lubricants evaluated during the exploratory tests. This paper also reports that while molybdenum disulfide appears to have qualities that induce slippage when used on housings or plain surfaces, it does not appear to reduce fretting in ball bearings subjected to small angle oscillation when used in dry powder form.

In contrast to this conclusion regarding molybdenum disulfide, Godfrey and Bisson (Reference 44) report that a bonded MoS_2 coating delayed fretting for 28,000,000 cycles for steel against glass and about 10,000,000 cycles for steel against steel. Dry MoS_2 , and mixtures with various carriers (water and aerosol, oil, and grease) also appreciably delayed fretting. Microscopic examination, however, indicated the MoS_2 may have been ineffective at the contact area, and that the carrier alone may have been responsible for the beneficial action. Without an inhibitor, the specimens fretted immediately.

McDowell (Reference 51) reports tests using dry molybdenum sulfide and tungsten sulfide powders. He states that there is a definite improvement when these dry lubricants are used. When tungsten sulfide was bonded to the surface, for example, it took 4.5 times as long to produce a severe case of fretting as it did with a standard specimen.

It is to be noted that in neither of these two examples was the data obtained on an actual anti-friction bearing.

A fretting corrosion research program involving lubricant evaluations has been conducted by the Coordinating Research Council using a Fafnir Thrust Ball Bearing Test Machine. Only greases have been evaluated in this program. It is interesting to note that an angle of oscillation of ± 6 degrees and a load of 550 pounds were selected for the tests, since these values showed up the greatest difference between greases. Results of this program are reviewed in Reference 78.

In general, it was found that feedability, or the ability of the lubricant to replenish itself, was the most important factor in mitigating fretting corrosion. Three methods of achieving this are: (1) By use of a soft grease, (2) by use of a shear susceptible grease, and (3) by use of a lubricant that permits bleeding of an oily phase (Reference 53).