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AN ANALYSIS OF FRETTING DAMAGE ON FATIGUE STRENGTH

by

Hsing-Chung Yeh
Department of Theoretical and Applied Mechanics

ABSTRACT

The mechanisms of fretting and fretting fatigue are briefly reviewed. Seven important variables which influence fretting fatigue strength are discussed and various methods of minimizing fretting damage are presented. Based on the observed facts from previous investigations, an hypothesis is proposed to estimate fretting fatigue strength. Because frictional phenomena for various contact material combinations are important factors in estimating fretting damage, an apparatus was designed to determine the coefficient of friction under specified fretting conditions. Two sets of data on long-life fretting fatigue strength, obtained by experiment, are compared with predicted values resulting from the hypothesis. The predicted values and experimental results are found to be in good agreement.

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I. INTRODUCTION

Fretting is a form of surface damage which occurs when two surfaces in contact undergo repeated sliding or rubbing motion. In metals, high spots or "asperities" on the surfaces in contact may undergo cold welding and be sheared off. In air, these small bits are readily oxidized, in the case of steel or aluminum, and debris in the form of brown or blackish powder appears. This is known as fretting corrosion. Accompanying this action, small surface cracks may be produced which can grow, under fatigue loading, and substantially reduce the normal fatigue strength of the material. Production of an oxide debris does not appear to be a necessary part of the fretting fatigue damage process, since fretting experiments conducted in an inert atmosphere or vacuum continue to show serious loss of fatigue strength with no debris production.

In service, fretting fatigue failures are found in assemblies, such as clamped or bolted joints and press fits of wheels or gears on rotating shafts. In small scale laboratory fatigue testing, it becomes more of a nuisance than a safety hazard, since it can lead to unexpected failures in the grip region rather than the test section of the specimen.

Fretting fatigue is a serious industrial problem which deserves particular attention, since reductions in fatigue strength to only 20 percent of the original value may occur under some service conditions.

Considering the fact that fretting fatigue is a rather common industrial problem, it is surprising that only a few reports have been published on this subject in the United States in the last decade. By contrast, the Japanese and British have devoted considerable effort to fretting research in recent years. One factor contributing to a lack of enthusiasm for research on this topic may be the lengthy list of variables which have been reported to have a significant effect on fretting fatigue strength. With the advent

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LIST OF SYMBOLS

σ_{max}	Maximum stress at a notch, N/m^2
ρ	Crack-tip radius, m
K_I, K_{II}, K_{III}	Stress intensity factor of Mode I, Mode II and Mode III, $MN/m^2\sqrt{m}$
τ_{net}	Net-section frictional stress across a junction, N/m^2
a	Half length of a junction or average radius of contact points, m
S	Standard deviation of surface roughness, m
t	The ratio of separation of two surfaces to the standard deviation of surface roughness
θ	Base angle of conical asperities
H, H_1, H_2	Maximum height of asperities defined in Japanese Industrial Standard, μm
W	Applied normal load, N
L_x L_y	Apparent contact area, m^2
P_m	Flow pressure of metal, N/m^2
σ_y	Yield strength of metal, N/m^2
P_{mf}	Flow pressure of the weaker metal in the presence of a frictional force, N/m^2
f	Coefficient of friction
A_r	The real contact area without friction, m^2
A_{rf}	The real contact area with friction, m^2
T	Frictional force between contacting materials, N
γ_{max}	Plastic zone size, m
ΔK_{th}	Threshold stress intensity factor, $MN/m^2\sqrt{m}$
C	Finite width correction factor
a_c	Critical crack size for propagation, m
$\Delta\sigma$	Applied stress range, N/m^2

of new research tools, such as the scanning electron microscope, and improved understanding of factors, such as surface residual stress and fracture mechanics aspects of crack propagation, it is believed that the list of critical variables for fretting fatigue can be reduced to a manageable level.

II. LITERATURE REVIEW

A. Mechanisms of Fretting

Fretting was first mentioned in the literature about sixty years ago when Eden, Rose, and Cunningham (1)* conducted fatigue tests to determine the endurance limit of metals. They noted corrosion of their test pieces and holders and suggested it was associated with the application of alternating stress. Since then, many investigators have studied fretting phenomena and have proposed various theories to explain fretting damage. Reviews such as those by Campbell (2), Allsop (3), Hurricks (4), Sachs and Horger (5), Yeh and Sinclair (6), and Wright (7, 8) have summarized the theories and important test results. The most detailed and complete work to date is a monograph by Waterhouse (9).

In 1927 Tomlinson (10) determined fretting to be the cause of rusting of steel surfaces in relative motion at their common points of contact. He suggested that the damage was a result of molecular cohesion between the surfaces and noted that it could be observed even when the relative displacement was as small as 2 nm (nanometer). Later Tomlinson, Thorpe, and Gough (11) investigated the fretting corrosion of closely fitting surfaces and suggested that the corrosion was mechanical rather than chemical in character. They decided that some surface slip, alternating in direction, was a necessary condition to cause damage.

Uhlig (12, 13, 14) reviewed the existing facts and suggested that the mechanism of fretting corrosion included a chemical factor and a mechanical factor, with observed damage, in general, resulting from both. An asperity rubbing on a metal surface is considered to produce a track of clean metal which is immediately oxidized, or upon which gas is rapidly adsorbed. The next asperity wipes off the oxide or initiates

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*Numbers in parenthesis designate references at the end of this text.

reaction of metal with adsorbed gas to form oxide and thus provide a chemical factor of fretting. Asperities also dig below the surface to cause a certain amount of wear by welding or shearing action in which metal particles are dislodged and this accounts for a mechanical factor as well. Uhlig suggested a quantitative expression describing weight loss through fretting corrosion as a function of load, number of cycles, slip distance, frequency and several material constants.

Wright (15, 16) studied ferrous surfaces fretting in air by making continuous electrical resistance measurements of the junction and showed that the metallic contact was quickly broken and the surfaces soon separated by a layer of ferric oxide. Oxidation processes were considered to play an important role in fretting corrosion. Oxidation was not an essential factor for fretting damage to occur but, in general, the extent of the damage was increased when it was present.

From the fact that fretting corrosion of steel was reduced in a nonoxidizing atmosphere, Waterhouse (17, 18) suggested that three possible processes were involved:

(1) mechanical abrasion by grinding or welding,

(2) abrasion by hard particles of oxide, and

(3) continual mechanical rupture of otherwise protective oxide films.

He proposed that fretting damage in air was largely due to a chemical process and that the first two processes were not as important as the third.

A mechanism of fretting based on the mechanism of wear was suggested by Feng and Rightmire (19). According to this proposal, when contacting asperities carry a normal load great enough to cause plastic deformation, the interface of asperities will be roughened by the deformation. This roughening of the interface produces a mechanical interlocking effect and application of a tangential force would shear off the peak of a high spot, which would then become a loose wear particle.

The process then continues through a period during which the accumulation of wear particles shift the wear action to abrasive action. Finally a state is reached in which damage is almost entirely caused by abrasion.

Holliday and Hirst (20) conducted fretting corrosion experiments on mild steel and concluded that fretting corrosion involved a sequence of processes. The first stage is one of plastic flow of the surface contact points leading to the formation of intermetallic junctions. After welding, the junctions rupture leading to the production of loose metallic fragments and to scarring the opposing metal surfaces. The presence of loose oxidized debris which accumulates and tends to roll between the rubbing contacts would reduce the coefficient of friction. If the debris prevents metallic contact, the mild wear mechanism persists at loads far in excess of those in which continuous sliding brings a change to severe wear.

Through damage measurements and the use of the scanning electron microscope, Bill (21) concluded that fretting occurs as a sequence of three mechanisms. First, fretting damage is initiated by an adhesion junction growth fracture process, much as in unidirectional sliding, in the first few hundred fretting cycles. Second, the cyclic stresses associated with the fretting motion leads to the development of a fatigue process, which is clearly in evidence after a thousand cycles. Third, fretting in air produces significant amounts of loose oxidized debris.

From the foregoing brief reviews it can be seen that there is some difference of opinion concerning the role of oxidation during fretting and its effect on subsequent damage. The evidence suggests that oxidation and accelerated wear concepts may operate simultaneously.

B. Mechanisms of Fretting Fatigue

There are few studies dealing with the fundamental mechanism of fretting fatigue. Horger (22) studied the effect of fretting corrosion on the fatigue strength of press-fitted

axle shafts. As the shaft rotated the alternating contraction and elongation of the axial fibers produced a minute sliding action on the end portion of the hub. Horger suggested this periodic sliding under pressure led to a "molecular plucking" of the surface metal and ultimately to fatigue crack initiation. Once fatigue cracks are initiated in the fretting region at relatively low stresses, then occasional higher stresses will propagate such incipient cracks to failure.

Based on an analysis of experimental results, Liu, Corten, and Sinclair (23) suggested that the primary mechanism responsible for fretting damage was the repeated frictional shear stress on the asperities or surface "high spots" which were in contact. Based on prevention of fatigue crack initiation by this mechanism, a mathematical expression was proposed which relates the fretting fatigue strength to the fatigue limit of the specimen material, the hardness of the gripping material, and the coefficient of friction.

In a study of a medium carbon and two low alloy steels using a cylindrical steel shoe on a plate, Nishioka and Hirakawa (24, 25, 26) reported that microcracks initiated but did not propagate to complete fracture after 10^7 cycles. Fatigue cracks were observed in the early stage of fretting. They note that the phenomena that cracks which had initiated in the early stage and did not propagate was similar to the behavior of fatigue cracks that have been observed in specimens with very sharp notches (non-propagating cracks). They analyzed the stress state in the fretted region and defined a stress concentration factor, K_t, and concluded that the initiation of fatigue cracks at low alternating stress under fretting conditions was due to high stress concentration at the contact surface caused by the frictional force of fretting. The occurrence of cracks seemed to depend on the stress state but not on the materials. The influence of fretting on the stress state is limited to only a very thin surface layer of the specimen. After a slight crack growth from the surface, there exists no influence of fretting on the stress state which controls the <u>propagation</u> of fatigue cracks.

In a study of a 0.7% carbon steel Waterhouse and Taylor (27) concluded that the origin of fatigue cracks in fretting fatigue is the boundary between the slip and non-slip areas in the contact region. They arise at this boundary because of high stress concentration. When a crack is formed it relieves the stress concentration at this point and the boundary between the slip and non-slip areas moves inwards resulting in the initiation of another crack which propagates more rapidly than the first crack because of the higher stress concentration. They suggest that crack formation can be prevented or retarded by insuring that slip occurs over the entire contact region.

Hoeppner and Goss (28, 29) suggested that fretting fatigue was a result of mechanical effects between the contact surfaces and that chemical factors were a secondary consideration. They also suggested that small cracks are initiated at points of high stress concentration near contacting asperities.

Two postulated mechanisms of fretting fatigue were examined experimentally by Collins and Tovey (30). First, an abrasive particle pit-digging mechanism and second, an asperity contact-microcrack initiation mechanism were studied. From experimental results it was concluded that the asperity contact-microcrack initiation mechanism was dominant. Furthermore, it was found that the direction of subsequent fatigue loading had a marked influence on fatigue strength. Fretting in the same direction as subsequent fatigue loading produced the greatest loss of strength.

C. Factors Influencing Fretting Fatigue Strength

One of the first systematic investigations of fretting fatigue was carried out by Peterson and Wahl (31) who studied the fatigue of shafts at fitted members. Since that time, investigators have reported a great many factors which affect fretting fatigue damage. Rimbey (32), for example, has compiled a listing of 42 variables from a review of the literature. This extensive listing, however, appears to contain

many redundant factors or items of questionable importance. The list of variables which have been demonstrated to be important by a majority of investigators is much shorter and can be summarized as follows.

1. Relative Slip Amplitude

Fenner and Field (33) found that the fretting fatigue strength of aluminum alloy, based on failure of the specimen, decreased with increasing relative slip amplitude. When the amplitude was greater than 15 microns (1 micron = 10^{-4} cm), they found no further reduction in fretting fatigue strength as is illustrated in Fig. 1. Nishioka and Hirakawa (34, 35, 36) reported essentially the same results based on the failure of medium carbon steel specimens. However, the fatigue stress at which surface cracks are initiated appears to go through a minimum at a relative displacement of 15 microns. The crack initiation stress appears to increase for larger displacement, but this observation may be due to the fact that wear processes dominate at large slip. Fretting cracks, once formed, would be quickly worn away. The fact that the curves based on failure of the specimen reach a minimum at 15 microns of relative slip and remain low thereafter, as the slip amplitude is increased, supports this viewpoint.

2. Clamping Pressure

Corten (37) studied fretting fatigue strength of 2024 ST aluminum alloy and found that the clamping pressure influenced fatigue strength only at very low values of less than 50 MN/m^2. Beyond that level, increased clamping pressure resulted in little further reduction of fatigue strength. Essentially the same results were obtained later by Liu, Corten, and Sinclair (23) on a Titanium alloy and by Nishioka and Hirakawa (38) on medium carbon steels. Goss and Hoeppner (39) also have shown the effects of clamping pressure on fretting fatigue strength in the low contact pressure range. This data is summarized in Fig. 2.

3. Contact Friction

Godfrey and Bailey (40, 41) studied the coefficient of friction and damage to contact area of different material combinations during the early stages of fretting. Since the formation of fretting fatigue cracks appears to be associated with the cold welding of asperities and since this cold welding phenomena or tendency should be reflected in the coefficient of friction, some recent workers have begun to study coefficient of friction under dynamic conditions as a function of number of cycles. Nishioka and Hirakawa (25) found the coefficient of friction increased steadily and the relative slip decreased with an increasing number of cycles in the very early stages of testing. A saturation value of the coefficient of friction was achieved at something less than 1000 cycles. The material used in their investigation was a steel.

Milestone (42, 43) used a specially designed apparatus to study the coefficient of friction in fretting joints and had essentially the same results, as illustrated in Fig. 3. The materials employed in his study were a 7075 T6 aluminum alloy and a Titanium 6 aluminum 4 vanadium alloy. It appears that for the purpose of fretting fatigue analysis, which usually concerns itself with lifetimes in excess of 10^5 cycles, we may consider that the contact friction remains at a saturation value, since fretting debris is accumulated between the contact surfaces and the frictional force stabilizes at some maximum value.

4. Materials of Mating Parts

The effect of material combinations on fretting fatigue strength can be classified into three categories:

(a) same material combinations (16, 23, 28-30, 37, 44-52, 64),

(b) the specimens harder than pads (23, 37, 53), and

(c) the pads harder than specimens (23, 51, 53, 64).

Tables 1 through 6 summarize results from the literature. Selected data are plotted in Figs. 4 through 7. In the first case, same material combinations, two different groups will be discussed. For steels, there is a linear relation between fretting fatigue strength and its ultimate strength as shown in Fig. 4. For the non-ferrous metals, the percentage of fretting to ordinary fatigue strength is linear with their Vicker's hardness number as shown in Fig. 5. For low strength materials, such as copper alloys and aluminum alloys, the fretting fatigue strength decreases rapidly with increasing hardness number of contacting materials. However, high strength materials such as Titanium alloys show less variation in fretting fatigue strength as the hardness of contacting material increases. In the second case, with the specimens harder than pads as shown in Fig. 6, the fretting fatigue strength increases with increased Vicker's hardness ratio of specimen to pad. When the specimen is much harder than the pad (i.e. $H_s/H_p > 5$), the fretting fatigue strength is practically unaffected. In the third case, for the pads harder than specimens as shown in Fig. 7, the fretting fatigue strength decreases with increased Vicker's hardness ratio of pad to specimen.

5. State of Stress and Residual Stress

The beneficial effects of a surface residual compressive stress in alleviating fretting fatigue are qualitatively well documented. The precise contribution of the surface residual stress is somewhat obscured by the fact that all methods commonly employed to produce the beneficial surface stress also result in increased surface hardness which is also beneficial. Shot peening, surface rolling, carburizing, nitriding, and surface induction hardening have all been reported to produce substantial increases in fretting fatigue strength. To date, no author has clearly documented the separate contributions of increased surface hardness and compressive surface residual stress.

In a related study Collins and Marco (44) used a two-step fretting fatigue test to study the effects of static pretension and static precompression of the specimen. In both cases the first step was fretting for 10^5 cycles under the prestress condition. The second step was a simple fatigue test of the fretted sample. They found that the reduction in fatigue strength was much greater for the case of the static precompressive stress than that of the static tensile prestress. In the case of static precompression, the fretting action produces a local high tensile stress in the surface when the prestress is removed. In the case of the static tensile prestress, fretting action results in a local residual compressive stress in the specimen when the prestress is removed. The results indicate that for this condition there was practically no reduction in fretting fatigue strength below that of the ordinary fatigue strength of the material.

Nishioka and Hirakawa (26) studied the effect of mean stress on fretting fatigue. They reported that the alternating stress amplitude, below which no fatigue cracks were initiated, was not affected by mean stress. The fatigue limit, however, based on propagation of minute cracks, decreases with an increase in tensile mean stress. Compressive mean stress retards propagation of the cracks and improves the fatigue limit. They decided that the influence of fretting on stress state was limited to only a very thin surface layer of the specimen. After a small amount of crack growth from the surface, there existed no influence of fretting on the stress state which controlled the propagation of fatigue cracks. The effect of clamping stress distribution was studied by Waterhouse (55). He found that the smaller contact areas needed a larger critical maximum pressure for crack propagation.

Waterhouse and Taylor (27) studied the origin of fretting cracks by means of the scanning electron microscope and concluded that the cracks originated in the boundary between slip and non-slip areas in the contact region. They state this should be a region of high stress concentration. When a crack is formed in this region, it

relieves the stress concentration and the boundary moves inward, resulting in the initiation of another crack which propagates more rapidly than the first.

6. Environment

Oding and Ivanova (53) have found that the fretting fatigue damage in air is greater than that in hydrogen. Waterhouse et al. (46) reported that if the material has a normally protective oxide film on the surface, corrosion fatigue is less damaging than fretting fatigue. However, if the material is not corrosion resistant, corrosion fatigue is more damaging than fretting fatigue.

Nishioka and Hirakawa (36) studied fretting fatigue of medium carbon steel in air and in an argon atmosphere and found little difference between the inert dry argon results and those of the oxidizing air atmosphere. They concluded that this was due to the fact that the mechanical damage process plays the major role in reducing the fatigue limit through fretting. The oxide debris is incidental to the fretting fatigue process and not a requirement for lowering fatigue strength. This conclusion is in agreement with the findings of Liu et al. (23).

7. Cyclic Frequency

Endo et al. (44) studied the effect of cyclic frequency on fretting fatigue strength of a 0.34 percent carbon steel. They found that the fretting fatigue damage increases with lower cyclic frequencies in both bending and twisting tests for the same number of fretting cycles. They reported that the fretting fatigue damage reaches a saturation value very early in the total fatigue life and the subsequent crack propagation period constitutes the larger portion of life. The lower the frequency, the shorter the saturation period for fretting fatigue crack formation.

D. Suggested Methods of Improving Fretting Fatigue Strength

Based on the foregoing observations of experimental data, some suggested methods of improving fretting fatigue strength are as follows.

1. Induce Surface Compressive Residual Stress

All methods commonly employed to induce surface compressive stress also produce increased surface hardness and, thus, provide a two-fold benefit.

(a) Shot peening (50) is reasonably effective and relatively inexpensive. It produces a shallow, work hardened, compressive surface layer which, on small components, can recover up to 50% of the normal strength loss due to fretting.

(b) Surface rolling (5, 56) with hardened rollers produces results similar to shot peening but is far more expensive. It is used when extra penetration and compressive layer depth are required, as in larger shafts and components. The effects of surface rolling can penetrate to 6 mm or more below the surface.

(c) Nitriding or carburizing followed by quenching can produce a shallow, very hard, wear resistant surface layer which is compressively stressed. It should be quite effective in raising the fretting fatigue strength of small components, but hard documentation is lacking.

(d) Surface induction hardening will produce results similar to carburizing in a much deeper surface layer. It should be better for larger components. While industrial application to fretting problems is common, quantitative data as to percent improvement to be expected is lacking.

2. Tensile Prestrain

Tensile prestrain accompanied by fretting produces a shallow, compressively stressed, surface layer in the fretted region. Laboratory results (54) show that the metal retains nearly 90% of the original fatigue strength, but it must be noted that the layer is very shallow and would eventually be worn away.

3. Sacrificial Shims

Sacrificial, soft metal shims or inserts of commercially pure aluminum or magnesium between the normal contacting surfaces can leave the fatigue strength at 95% to 100% of its normal value (23). The drawback to this technique is that the soft metal is fretted away and must be replaced periodically.

4. Lubrication

Lubrication reduces the coefficient of friction but ranges widely in effectiveness, depending on the character of the lubricant (57, 58). Improvement in fretting fatigue strength, due to treatment with oils or greases, ranges from zero to only a few percent. The high viscosity materials seem to do best but, in any event, improvement is only marginal.

Dry lubricants, such as molybdenum disulphide, are better able to resist high contact pressure, and improvements of up to 20% in fretting fatigue strength have been reported.

5. Special Surface Coatings

Special surface coatings remain a relatively unexplored area. Under relatively low contact pressures (7 MN/m^2), teflon coating produces good results until the teflon is worn through and contact of the base metals occurs. Thin coatings of soft metals such as aluminum provide little improvement in fretting fatigue strength

as they quickly wear away, although Bowers (50) shows some improvement following spraying with an aluminum, 1% zinc alloy in combination with shot peening. Hard metal plating (chromium) and flame spraying with tungsten provide little improvement in fretting fatigue strength. While the wear rate is reduced by these coatings, they apparently contain many surface fissures which soon lead to crack growth in the base metal. One exception to this experience with hard metal coatings is reported by Taylor and Waterhouse (47). They got a significant improvement in strength with a molybdenum coating on an En-8 steel (see Table 7).

III. ANALYSIS

From the results of previous investigators, the following facts have been established.

(1) Cracks are initiated at certain angles to the relative slip direction.

(2) Fretting fatigue strength decreases with increased contact pressure up to a limiting value.

(3) For a given gripping material, fretting fatigue strength decreases with decreased hardness of the specimen.

(4) For a given specimen, fretting fatigue strength decreases with increased hardness of gripping material.

(5) Some non-propagating cracks are found in fretted specimens.

Various investigators have studied fretting fatigue with particular reference to factors causing damage and the comparison of fatigue strength with and without fretting. None have employed the concepts of fracture mechanics to analyze the crack initiation phase caused by the repeated shear stress during fretting and the subsequent fatigue crack propagation.

Since the plastic zone size plays an important role in crack initiation, it is important to consider plastic zone sizes around the tips of contacting asperities during the fretting process. When two surfaces contact with a normal force, the asperities will form a cold junction, as shown in Fig. 8. If one of the surfaces is forced to slide back and forth against the other, a repeated shear stress will occur along the interfaces or inside the asperities, depending on the junction. Since the plastic zone size around the tips of contacting asperities will depend on the material properties and loading conditions, one should first study the relationship between plastic zone size and other variables.

A. Determination of Plastic Zone Size

In Hurrick's review article (4), microcracks are shown on a plane sectioned through the fretting area. The initiated microcracks result from the repeated shear stress acting on the cold-weld junction. During the fretting process, the normal contact pressure on each asperity may be considered constant. This leads to the repeated frictional force as the main variable which affects the maximum shearing stress on the fretting surface. Now consider Mode II Fracture behavior which corresponds to the present loading situation. This is the case when two equal and opposite stresses are applied along the edges of cracks. Failure under this type of loading is called Mode II Fracture and a corresponding stress intensity factor, K_{II}, may be determined.

The stress intensity factor of Mode II has been expressed (59) as

$$K_{II} = \lim_{p \to 0} \pi^{\frac{1}{2}} \sigma_{max} \rho^{\frac{1}{2}} \qquad [1]$$

provided $$K_I = K_{III} = 0$$

The maximum normal stress on an infinite sheet with load transmitted across a neck between hyperbolic notches as shown in Fig. 9 is expressed (59) as

$$\sigma_{max} = \frac{\left(\frac{a}{\rho} + 1\right)^{\frac{1}{2}}}{\left(1 + \frac{\rho}{a}\right) \tan^{-1} \left(\frac{a}{\rho}\right)^{\frac{1}{2}} - \left(\frac{\rho}{a}\right)^{\frac{1}{2}}} \tau_{net} \qquad [2]$$

Substituting Eq. [2] into Eq. [1] yields,

$$K_{II} = 2\tau_{net} \left(\frac{a}{\pi}\right)^{\frac{1}{2}} \qquad [3]$$

Equation [3] shows that two variables "τ_{net}" and "a" have to be determined to evaluate the magnitude of K_{II}.

1. Determination of the Average Radius of Contact Points

Tsukizoe and Hisakado (60, 61) calculated the average radius, "a", of contact points on the following assumptions.

(a) The distribution curve that is obtained from the profile curve of the surface has a normal distribution.

(b) The surface has the same profile curve in any direction.

(c) The surface contains a large number of asperities in the form of cones of the equal base angle.

(d) The deformation of the metal occurring at the contact is plastic.

The average radius of contact points is given (60, 61) as

$$a = \frac{S}{t \tan \theta} \qquad [4]$$

In Eq. [4] for two metal surfaces in contact, "tan θ" and "t" can be calculated from the following equations (61)

$$\tan \theta = \frac{\pi}{2} \frac{\sqrt{H_1^2 + H_2^2}}{3.48\sqrt{H_1^2 + H_2^2} + 23.46} \qquad [5]$$

$$t = \frac{1}{2} - \frac{W}{L_x L_y P_m} \qquad [6]$$

Substituting Eq. [6] into Eq. [4], we have

$$a = \frac{S}{\left(\frac{1}{2} - \frac{W}{L_x L_y P_m}\right) \tan \theta} \qquad [7]$$

2. Correction of the Average Radius of Contact Points Due to the Existence of a Frictional Force

From the plastic indentation of metals (62), we have

$$P_m = 3\sigma_y \qquad [8]$$

Shaw (63) has shown that flow pressure changes with the coefficient of friction and can be expressed as

$$P_{mf} = \frac{3\sigma_y}{1 + f^2} \qquad [9]$$

Hence, the real contact area is given by

$$A_r = \frac{W}{P_m} = \frac{W}{3\sigma_y} \text{ (without friction)} \qquad [10]$$

$$A_{rf} = \frac{W}{P_{mf}} = \frac{(1 + f^2)\, W}{3\sigma_y} \text{ (with friction)} \qquad [11]$$

In Eq. [7], the quantity $W/L_x\, L_y\, P_m$ is the ratio of true contact area to apparent contact area under the condition of zero frictional force. In the presence of frictional force, we have to change A_r to A_{rf} and the ratio becomes $W/L_x\, L_y\, P_{mf}$. Hence, Eq. [7] should be written as

$$a = \frac{S}{\left(\frac{1}{2} - \frac{W}{L_x\, L_y\, P_{mf}}\right) \tan\theta}$$

$$= \frac{S}{\left(\frac{1}{2} - \frac{(1 + f^2)\, W}{3 L_x\, L_y\, \sigma_y}\right) \tan\theta} \qquad [12]$$

From Eq. [12] if the surface profile, standard deviation, maximum height of asperities are measured and the coefficient of friction is determined under the applied normal load, it is possible to calculate the average radius of junctions.

3. Determination of Shear Stress on the Junction

The frictional force, T, is determined from experiment. The actual contact area, A_{rf}, also can be determined from the determination of the coefficient of friction. Hence, the net-section frictional stress across a junction is

$$\tau_{net} = \frac{T}{A_{rf}}$$

$$- \frac{fW}{\frac{(1+f^2)\,W}{3\sigma_y}} = \frac{3f\sigma_y}{1+f^2} \qquad [13]$$

4. Determination of Plastic Zone Size

Substituting Eqs. [12] and [13] into Eq. [3], we have

$$K_{II} = 2\tau_{net}\left(\frac{a}{\pi}\right)^{\frac{1}{2}}$$

$$= 2\,\frac{3f\sigma_y}{1+f^2}\left[\frac{S}{\pi\left(\frac{1}{2} - \frac{(1+f^2)\,W}{3\sigma_y\,L_x\,L_y}\right)\tan\theta}\right]^{\frac{1}{2}}$$

$$= \frac{6f\sigma_y}{1+f^2}\left[\frac{S}{\pi\left(\frac{1}{2} - \frac{(1+f^2)\,W}{3\sigma_y\,L_x\,L_y}\right)\tan\theta}\right]^{\frac{1}{2}} \qquad [14]$$

For Mode II the plastic zone size, γ_{max}, is written as

$$\gamma_{max} = \frac{2}{\pi}\left(\frac{K_{II}}{\sigma_y}\right)^2 \qquad [15]$$

Substituting Eq. [14] into Eq. [15], we have

$$\gamma_{max} = \left[\frac{6f}{\pi(1+f^2)}\right]^2 \frac{2S}{\left[\frac{1}{2} - \frac{(1+f^2)\,W}{3\sigma_y\,L_x\,L_y}\right]\tan\theta} \qquad [16]$$

Equation [16] shows how the maximum plastic zone size can be determined if the surface-roughness-standard-deviation, the coefficient of friction, the maximum height of asperities, H, and the loading condition are given. For example, in this

study SAE 4340 steel has the corresponding data as

$$W = 2220 \text{ N} \qquad L_x L_y = 2 \times 10^{-5} \text{ m}^2$$

$$f = 0.7 \qquad S = 0.4 \times 10^{-6} \text{ m}$$

$$\sigma_y = 1100 \text{ MN/m}^2 \qquad \tan\theta = 0.18$$

Substituting these values into Eq. [16], we have

$$\gamma_{max} \approx 9 \times 10^{-6} \text{ m} \qquad [17]$$

B. Estimation of Fretting Fatigue Strength

From the threshold stress intensity factor, we may estimate the maximum crack size which will not propagate under a given loading condition by

$$\Delta K_{th} = C \Delta\sigma \sqrt{\pi a_c} \qquad [18]$$

or

$$a_c = \left(\frac{1}{\pi}\right)\left(\frac{\Delta K_{th}}{C \Delta\sigma}\right)^2 \qquad [19]$$

The value of "C" in Eqs. [18] and [19] is approximately "1" for a center crack in a wide plate. If we assume C = 1 to analyze fretting fatigue data, the following relations will be established. For SAE 4340 steel ΔK_{th} is equal to 3.3 $\text{MN/m}^2\sqrt{\text{m}}$ and also for this material VHN is equal to 240. The ultimate strength is approximately 765 MN/m^2. From Fig. 4 the fretting fatigue strength is about 20% of the ultimate strength. Hence, the fretting fatigue strength, $\Delta\sigma/2$, is nearly 150 MN/m^2, or $\Delta\sigma = 300 \text{ MN/m}^2$. Substituting $\Delta K_{th} = 3.3 \text{ MN/m}^2\sqrt{\text{m}}$, $C = 1$, $\Delta\sigma = 300 \text{ MN/m}^2$ into Eq. [19], we have

$$a_c = 38 \times 10^{-6} \text{ m} \qquad [20]$$

Comparing Eqs. [17] and [20] yields

$$a_c = 4\gamma_{max} \qquad [21]$$

which corresponds to a critical crack size larger than the calculated plastic zone size. In the case of a regular finite width, the correction factor C is larger than 1. Hence, the value of a_c in Eq. [21] should be slightly less than $4\gamma_{max}$. From the experimental results discussed in the later parts, if we analyze fretting fatigue data in the literature and assume

(1) standard deviation of surface roughness

$S = 0.5 \times 10^{-6}$ m

(2) $\tan\theta = 0.15$

(3) $f = 1.0$ for Titanium alloys

$f = 0.7$ for steels

Then the maximum plastic zone sizes and critical crack sizes can be calculated. Results from these calculations are presented in Tables 8 and 9 and we find that

$$\frac{a_c}{\gamma_{max}} \approx 1.2 \left(\frac{\Delta K_{th}}{\Delta K_o}\right)$$

or

$$a_c \approx 1.2 \left(\frac{\Delta K_{th}}{\Delta K_o}\right) \gamma_{max} \qquad [22]$$

Substituting Eq. [21] into Eq. [18] and setting C = 1, we have

$$\Delta\sigma = \frac{\Delta K_{th}}{\sqrt{\pi a_c}}$$

$$= \frac{\Delta K_{th}}{\sqrt{\pi \times 1.2 \frac{\Delta K_{th}}{\Delta K_o} \gamma_{max}}}$$

$$= \frac{1}{2}\sqrt{\frac{\Delta K_{th}\,\Delta K_o}{\gamma_{max}}} \qquad [23]$$

From Eq. [23], we conclude that plastic zone size plays an important role in the estimation of fretting fatigue strength. Once the plastic zone size is determined under specified conditions, the fretting fatigue strength can be deduced. For a given material and loading condition, σ_y, P, S, H are known, the only unknown which has to be determined is the coefficient of friction f.

IV. EXPERIMENTAL PROCEDURES

The experimental procedures performed in this study are described as follows.

A. Preparation of Specimens and Mating Pads

Specimens and mating pads were machined as shown in Figs. 10 and 11. Before testing, each specimen was polished with 320 and 600 grit grinding paper and then cleaned with acetone and ethyl alcohol to ensure clean surfaces. The hardnesses of specimens and pads were then determined with a Rockwell hardness tester. The surface profiles were examined with a Dektak profilometer (an instrument for measurement of surface profiles). The standard deviation, S, for the surface profile was calculated and maximum height of asperities*, H, (60) was also determined.

B. Determination of Coefficient of Friction between Contact Materials

Fretting tests were performed on an MTS closed-loop axial hydraulic material testing system which provided a longitudinal oscillating motion. In order to assure accurate alignment, the bottom part of the specimen was held in a Wood's metal grip (65). The desired normal pressure between the fretting specimens and gripping pads was obtained using a specially designed apparatus. With the help of a strain gage indicator, the calibrated load cells, a strip chart recorder, and an oscilloscope, normal forces and frictional forces could be determined. The experimental set up

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*In accordance with the Japanese Industrial Standard, maximum height of asperities, H, is the difference between the highest peak and lowest valley in a profile of a measured length. The standard of the measured lengths, L, are:

$L = 0.3$ mm for $H < 0.8$ μm
$L = 0.1$ mm for 0.8 μm $< H < 6$ μm
$L = 3.0$ mm for 6 μm $< H < 25$ μm

and its schematic diagram are shown in Fig. 12 through Fig. 14.

For the tests at room temperature in air environment, the relative displacement between pad and specimen, the contact pressure and cyclic frequency were controlled. For the purpose of controlling relative displacement, an Instron extensometer was used. The displacement was calibrated against a mechanical dial to an accuracy within two microns. These tests were performed for different hardnesses of materials which included SAE 1020 carburized steel, SAE 1020 carburized steel with a layer of electroless nickel, SAE 1020 carburized steel with a luburized phosphate coating, and SAE 4340 steel. The surface hardness of these materials is shown in Table 10.

In the determination of the coefficient of friction, the number of fretting cycles was allowed to increase until a constant value of the coefficient of friction was reached. This number of fretting cycles varied from a few hundred cycles to several hundred cycles, depending on the test conditions. In tests to determine when cracks are initiated, a larger number of fretting cycles are necessary.

C. Metallography

The fretted surfaces were examined with an optical microscope to record surface phenomena due to fretting damage at different stages. Particular attention was paid to the boundary between the damaged and undamaged area. For severely damaged surfaces, low magnification was used to reveal the whole damaged area. In examining the fretted surfaces, any crack-like flaws or pit formations were examined carefully and recorded.

V. RESULTS AND DISCUSSION

A typical surface profile of a specimen (No. UIS 17) is shown in Fig. 15. The surface roughness, roughness standard deviation, and maximum height of asperity are obtained from this measurement. The results calculated from the measurement are: surface roughness = 1.7 μm, roughness standard deviation S = 0.4 μm, maximum height of asperities H = 3 μm, and tan θ = 0.18.

A. Coefficient of Friction

In the determination of the coefficient of friction in a specified test condition, normal force and frictional force are recorded simultaneously as a function of the number of fretting cycles. Figure 16 shows the relationship between frictional force, normal force, and fretting cycles. The coefficient of friction, f, is determined by the ratio of frictional force to normal force. The results show the frictional force increases to an upper limit with an increasing number of fretting cycles, whereas the normal force remains constant until a larger number of fretted cycles is attained. It is believed that this small variation in normal force is caused by wear damage on the surface as the test continues.

The general trend of the relationship between coefficient of friction and fretting cycles is shown in Figs. 17 through 19. The coefficient of friction increases with increasing fretting cycles until it reaches a saturation value. This indicates that the coefficient of friction varies with different loading conditions. For the same contact pressure, the larger the relative slip amplitude, the greater is the value of the coefficient of friction. Since the wear process is dominant in the case of very large relative slip amplitudes (larger than 125 μm), the friction-cycle behavior is different from that with small relative slip amplitudes.

For a specified test condition (contact pressure = 110 MN/m^2), the saturation values of the coefficient of friction for SAE 4340 steel are plotted against relative

slip amplitude in Fig. 20. It can be seen that higher cyclic frequencies are associated with the lower coefficient of friction. There exists a linear relationship between the coefficient of friction and the relative slip amplitude for the magnitude of relative slip less than 100 μm. At relative slip amplitudes greater than 100 μm, a constant or "saturation" value of the coefficient of friction is found. It has been reported (25, 41, 43) that the coefficient of friction for steel against steel is nearly 0.7. This is because most investigations into friction phenomena use large relative slip amplitude tests and/or unidirectional sliding. It is understood that fretting damage occurs under very small relative slip amplitudes. Hence, the determination of the coefficient of friction within the small amplitude unsaturated range is very important.

The effect of hardness of the specimen on the coefficient of friction under different test conditions is shown in Figs. 21, 22, and 23. When comparing Curve A and B in Fig. 21, the harder specimen has the lower value of the coefficient of friction. Curves C and D show lower values of the coefficient of friction, even though the hardnesses are greater than that of the specimen of Curve A. The reason for this is that the surfaces of specimens of Curve C and D have been treated with electroless nickel plating and phosphate coating respectively. The treated surfaces have less frictional resistance than the untreated ones because the coating acts as a lubricant. Figures 22 and 23 show the same result. Additionally, it may be noted that the small relative slip amplitudes are associated with the smaller values of the coefficient of friction. It is clear that frictional force changes with the test condition, and the relative slip amplitude dominates the value of coefficient of friction.

The effects of relative slip amplitude on the coefficient of friction under specified test conditions can also be found in Fig. 24 to Fig. 27. The data show that the coefficient of friction increases with the relative slip amplitude. When the coefficients of friction are plotted against hardness of specimen as shown in Fig. 28, the larger

relative slip amplitude is associated with the greater value of coefficient of friction. However, the softer the specimen, the greater the coefficient of friction under the same relative slip amplitude.

B. Metallographic Analysis

Both optical microscopy and scanning electron microscopy are very useful in the study of fretting damage surfaces. Recently, SEM has been extensively used to reveal any initiated cracks (21, 27, 66, 67). Conventional optical microscopy is used to reveal large crack sizes. Nishioka and Hirakawa (25) were able to find surface cracks on fretted fatigue surfaces of medium carbon steel. In order to check whether cracks are initiated by fretting action only, the present specimen surfaces were examined with an optical microscope.

In the present work, several different test conditions as well as different contacting materials were employed. There are several phenomena which have been observed.

1. Location of Cracks

Although cracks were found on the boundary between slip and non-slip regions on several specimens, this was not frequent enough to state fretting action alone will initiate cracks without any restrictions. The possible reasons for not finding large size cracks are:

(a) Because the purpose of this experiment primarily was to determine the saturation value of coefficient of friction between contacting materials, the number of fretting cycles employed in the tests was less than 10^5 cycles. Fretting cracks may require a larger number of cycles to initiate.

(b) The tiny cracks resulting from fretting action are either too small to reveal without some special technique or require more than 10^4 cycles to form.

(c) Hard specimens have small coefficients of friction and a small plastic zone which has major effects in reducing the size of initiated cracks.

2. Severity of Damage

Softer materials received more severe fretting damage. The fretted surfaces of SAE 4340 steel (VHN = 240) were more severely damaged than those surfaces of SAE 1020 carburized steel (VHN = 870), SAE 1020 carburized steel with electroless nickel plating (VHN = 717), and SAE 1020 carburized steel luburized with phosphate coating. There were only slight scratch traces on the surfaces of these specimens which had special surface preparations. This may be due to the harder specimens having larger wear resistance. For the very large relative slip amplitude (larger than 100 μm), it is believed that severe wear action prevents the observation of tiny cracks within the contact surface. There were wave-like markings just beyond the damaged boundary resulting from the severe damage inside the boundary.

From the observed facts in this investigation, a conclusion is drawn that fretting cracks usually require more than 10^4 cycles to initiate, and they usually occur on the boundary between the slip and non-slip region.

C. Comparison of Fretting Fatigue Strength-Experimental Results Versus Calculation from Eq. [23]

The analysis in Chapter III suggests that fretting fatigue strength can be estimated by applying Eqs. [16] and [23].

1. Same Contact Material and Hardness

Specimen:	SAE 1045 steel	Hardness: R_c 55 (VHN = 595)
Pad:	SAE 1045 steel	Hardness: R_c 55

Contact Pressure: $20.7\ MN/m^2$

Relative Slip Amplitude: $25\ \mu m$

Coefficient of Friction, $f = 0.15$ (estimation from data of Fig. 28)

Standard Deviation, $S = 0.5 \times 10^{-6}\ m$ (estimation from data of Fig. 15)

$\tan\theta = 0.15$ (estimation from data of Fig. 15)

Substituting these values into Eqs. [16] and [23], we have

$$\gamma_{max} = 1.05 \times 10^{-6}\ m$$

and

$$\Delta\sigma = \frac{1}{2}\sqrt{\frac{\Delta K_o\ \Delta K_{th}}{\gamma_{max}}} = \frac{1}{2}\sqrt{\frac{1 \times 3.3}{1.05 \times 10^{-6}}}\ \frac{MN}{m^2} = 890\ \frac{MN}{m^2}$$

$$\therefore \text{ Fretting fatigue strength, } \frac{\Delta\sigma}{2}, = 445\ \frac{MN}{m^2}$$

The experimental result obtained by G. Roberts (64) was $470\ MN/m^2$.

2. <u>Same Contact Material but Different Hardness</u>

Specimen: SAE 1045 steel Hardness: R_c 35 (VHN = 345)

Pad: SAE 1045 steel Hardness: R_c 55

Contact Pressure: $20.7\ MN/m^2$

Relative Slip Amplitude: $25\ \mu m$

Coefficient of Friction: $f = 0.2$ (estimation from data of Fig. 28)

Standard Deviation, $S = 0.5 \times 10^{-6}\ m$ (estimation from data of Fig. 15)

$\tan\theta = 0.15$ (estimation from data of Fig. 15)

Substituting these values into Eqs. [16] and [23], we have

$$\gamma_{max} = 1.85 \times 10^{-6}\ m$$

and

$$\Delta\sigma = \frac{1}{2}\sqrt{\frac{\Delta K_o \ \Delta K_{th}}{\gamma_{max}}} = \frac{1}{2}\sqrt{\frac{1 \times 3.3}{1.85 \times 10^{-6}}} \frac{MN}{m^2} = 680 \frac{MN}{m^2}$$

$$\therefore \text{ Fretting fatigue strength, } \frac{\Delta\sigma}{2}, = 340 \frac{MN}{m^2}$$

The experimental result obtained by G. Roberts (64) was 311 MN/m^2.
In the previous calculations, two estimated values $S = 0.5 \times 10^{-6}$ m and $\tan\theta = 0.15$ are used. These values correspond to those obtained in Fig. 15 for similarly finished surfaces. The difference in fretting fatigue strength between calculated and experimental results is within 10%. However, if the value of correction factor "C" in Eq. [19] were employed to correct for finite width, the predicted values should be still closer to the test results. It is assumed that Eqs. [16] and [23] can be employed to estimate fretting fatigue strength of the same material in contact.

The derivation of Eq. [12] is based on the assumption that the two contact materials have the same hardness. Hence, the formulas used to estimate fretting fatigue strength are mainly suitable for the same material combination. However, if two contact materials have a small difference in hardness, the formulas may still be applied. There are two extreme cases:

(a) For the pad much harder than specimen, the formulas are applicable.

(b) For the specimen much harder than the pad, there is probably no fretting fatigue strength reduction in the specimen, since a plastic zone "starting" crack will not be developed.

VI. SUMMARY AND CONCLUSIONS

A preponderance of evidence indicates that fretting fatigue is primarily a mechanical rather than a chemical problem. The process involves two stages:

(1) a crack initiation stage wherein small cracks are formed at regions of stress concentration near cold weld junctions, and

(2) a propagation stage wherein the minute cracks may be propagated to failure by the fluctuating nominal stress.

The prime variables controlling these processes are:

(a) the surface hardness or yield strength of the materials in contact,

(b) the contact pressure, and

(c) the coefficient of friction between the two.

Increasing surface hardness or yield strength, decreasing contact pressure and reducing coefficient of friction, all tend to reduce the "initiation" crack size of stage 1 and, consequently, improve fretting fatigue strength. Surface compressive residual stress fields can stop or retard propagation of these cracks in stage 2 and, thus, also increase fretting fatigue strength.

Case studies of successful "fixes" of fretting fatigue problems are neither numerous nor well documented; nevertheless, all appear to involve application of one or more of the aforementioned principles. Specific methods of improving strength vary widely in cost and effectiveness; each possesses its own special characteristics and drawbacks and, in general, the method selected is determined by the service conditions.

In order to estimate the fretting fatigue strength under a specified test condition, the following procedures are recommended:

(1) Record the surface profile, calculate the surface-roughness-standard-deviation and maximum height of asperity.

(2) Determine the coefficient of friction between two contact materials under specified test conditions such as relative slip amplitude, contact pressure, and cyclic frequency.

(3) Calculate plastic zone size from Eq. [16].

(4) Use equation

$$\Delta\sigma = \frac{1}{2}\sqrt{\frac{\Delta K_o \ \Delta K_{th}}{\gamma_{max}}}$$

to estimate fretting fatigue strength.

None of the above steps require any critical technique. It is suggested that these procedures can be used to estimate fretting fatigue strength providing test results are not available. For further work, additional long-term fretting fatigue tests need to be performed to check with the estimated values.

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67. D. W. Hoeppner and G. L. Goss, "Metallographic Analysis of Fretting Damage in Ti-6Al-4V MA and 7075-T6 Aluminum, Wear, Vol. 27, 1974, p. 175.

TABLE 1 FRETTING FATIGUE DATA - STEELS

Materials	Hardness (VHN)	Ultimate Tensile Strength (MN/m^2)	Contact Pressure (MN/m^2)	Ordinary Fatigue Strength** (MN/m^2)	Fretting Fatigue Strength** (MN/m^2)	Percentage of Fretting to Ordinary Fatigue Strength	Reference
18 Cr-8 Ni Stainless Steel	170	560	17.8	281	185	66	46
0.4% Carbon Heat Treated	414	1360	110.0	552	276	50	37
4340	345	1160	69.0	466	276	59	30
0.34% Carbon Heat Treated Oil Quenched Tempered	280	897	772.0	472	386	82	45
0.35% Carbon Normalized	170	575	77.2	286	248	87	45
En 8 Normalized	210	774	62.5	266	87	32	47
0.53% Carbon	160	638	705.0*	260	160	62	49
0.7% Carbon Cold Drawn	365	1360	62.5	525	140	27	48
0.7% Carbon Normalized	140	940	62.5	216	123	57	48
1045	595	1970	20.7	700	470	67	64

*Maximum Hertzian Pressure
**Based on 10^7 cycles

TABLE 2 FRETTING FATIGUE DATA - COPPER AND COPPER ALLOYS

Materials	Hardness (VHN)	Ultimate Tensile Strength (MN/m^2)	Contact Pressure (MN/m^2)	Ordinary Fatigue Strength (MN/m^2)	Fretting Fatigue Strength (MN/m^2)	Percentage of Fretting to Ordinary Fatigue Strength	Reference
Pure Copper	85	255	705.0*	83	62	75	49
70/30 Brass (Annealed)	75	328	62.5	89	76	86	48
70/30 Brass (Work Hardened)	160	508	62.5	139	92	66	48

*Maximum Hertzian Pressure

TABLE 3 FRETTING FATIGUE DATA - ALUMINUM ALLOYS

Materials	Hardness (VHN)	Ultimate Tensile Strength (MN/m^2)	Contact Pressure (MN/m^2)	Ordinary Fatigue Strength (MN/m^2)	Fretting Fatigue Strength (MN/m^2)	Percentage of Fretting to Ordinary Fatigue Strength	Reference
DTD 683	210	602	38.6	159	32	20	50
7075-T6	190	535	20.7	112	57	51	29
AA2024	180	525	38.6	150	59	40	50
L65	170	506	38.6	129	46	36	50
L65	170	506	3.86	131	62	47	16
2024ST	150	450	110.0	158	90	57	37
7075-T6	190	540	705.0*	165	68	41	49
Al-4Mg-0.7Mn	89	314	91.5*	100	100	100	51

*Maximum Hertzian Pressure

TABLE 4 FRETTING FATIGUE DATA - TITANIUM AND TITANIUM ALLOYS

Materials	Hardness (VHN)	Ultimate Tensile Strength (MN/m^2)	Contact Pressure (MN/m^2)	Ordinary Fatigue Strength (MN/m^2)	Fretting Fatigue Strength (MN/m^2)	Percentage of Fretting to Ordinary Fatigue Strength	Reference
Ti-6Al-4V (IMI 318)	335	1050	62.5	371	139	37	52
Ti-2.5 Cu (IMI 230)	228	578	62.5	278	124	45	52
Pure Titanium (IMI 130)	265	675	62.5	201	124	62	52
Ti-4Al-4MN (RC 130 B)	354	1160	104.0	614	248	40	23
Ti-6Al-4V	320*	975	20.7	360	125	35	29

*From ASM Metals Handbook, 8th Edition, Vol. 1, p. 1149

TABLE 5 DIFFERENT CONTACT MATERIALS - SPECIMENS HARDER THAN PADS

Materials: Specimen	Materials: Pad	Hardness (VHN): Specimen	Hardness (VHN): Pad	$\frac{H_s}{H_v}$	Contact Pressure (MN/m^2)	Ordinary Fatigue Strength (MN/m^2)	Fretting Fatigue Strength (MN/m^2)	Percentage of Fretting to Ordinary Fatigue Strength	Reference
0.4% Carbon Steel Heat Treated	70/30 Brass Cold Rolled	414	140	2.95	110	552	324	59	37
0.4% Carbon Steel Heat Treated	0.2% Carbon Steel Hot Rolled	414	130	3.18	110	552	448	81	37
0.4% Carbon Steel Heat Treated	2024ST Al Alloy	414	150	2.70	110	552	500	91	37
XH3M Steel	3% Si Transform Steel	217	176	1.23	---	264	186	70	53
Titanium RC 130 B	4340 Steel	354	238	1.48	276	615	145	23	23
Titanium RC 130 B	Lapelloy	354	207	1.71	276	615	193	31	23
Titanium RC 130 B	7075-T6 Al Alloy	354	194	1.82	104	615	262	43	23
Titanium RC 130 B	2011-T8 Al Alloy	354	126	2.81	104	615	552	90	23
Titanium RC 130 B	70/30 Brass	354	117	3.02	104	615	207	34	23
Titanium RC 130 B	Copper	354	96	3.68	104	615	496	81	23
Titanium RC 130 B	1100-F Aluminum	354	41	8.64	104	615	586	96	23
Titanium RC 130 B	Magnesium	354	39	9.08	104	615	586	96	23

TABLE 6 DIFFERENT CONTACT MATERIALS - SPECIMENS SOFTER THAN PADS

Materials: Specimen	Materials: Pad	Hardness (VHN): Specimen	Hardness (VHN): Pad	$\frac{H_p}{H_s}$	Contact Pressure (MN/m^2)	Ordinary Fatigue Strength (MN/m^2)	Fretting Fatigue Strength (MN/m^2)	Percentage of Fretting to Ordinary Fatigue Strength	Reference
XH4M Steel	Austenite 18-8	217	276	1.27	---	245	187	76	53
Titanium RC 130 B	4340 Steel	354	595	1.68	276.0	615	131	21	23
Titanium RC 130 B	4340 Steel	354	397	1.12	415.0	615	124	20	23
Titanium RC 130 B	4340 Steel	354	397	1.12	276.0	615	152	24	23
Titanium RC 130 B	4340 Steel	354	397	1.12	152.0	615	145	23	23
Titanium RC 130 B	4340 Steel	354	397	1.12	27.6	615	193	31	23
Al-4Mg-0.7Mn Al Alloy	Copper	89	90	1.01	91.5*	100	100	100	51
Al-4Mg-0.7Mn Al Alloy	Brass 70/30 Work Hardened	89	132	1.48	100.0	100	72	72	51
Al-4Mg-0.7Mn Al Alloy	Carbon Steel 0.6-0.7%C Normalized	89	133	1.50	112.0	100	66	66	51
1045 Steel	1045 Steel	345	595	1.73	20.7	538	311	58	64

*Maximum Hertzian Pressure

TABLE 7 THE IMPROVEMENT OF FRETTING FATIGUE STRENGTH BY SURFACE TREATMENT

Materials	Method of Treatment	Percentage of Fretting to Ordinary Fatigue Strength	Reference
DTD 683	None	20	50
	Shotpeened	60	50
	Alumina Blasted	70	50
	Alumina Blasted and Metal Spraying	90	50
Magnesium Alloys	None	35	5
	Surface Rolled	85	5
En 8 Steel	None	28	47
	Mo Coating	67	47

TABLE 8 THE RELATIONSHIP BETWEEN CRITICAL CRACK SIZE AND PLASTIC ZONE SIZE - STEELS

Materials	Hardness (VHN)	Contact Pressure (MN/m^2)	Fretting Fatigue Strength (MN/m^2)	Critical Crack Size (μm)	Plastic Zone Size (μm)	The Ratio of Critical Crack Size to Plastic Zone Size	$\frac{\Delta K_{th}^*}{\Delta K_o}$	Reference
0.4% Carbon Heat Treated	414	110.0	276	11.3	11.6	0.97	3.3	37
4340	345	69.0	112	68.8	11.3	6.1	3.3	30
En 8 Normalized	210	62.5	87	114.0	11.8	9.6	3.3	47
0.7% Carbon Cold Drawn	365	62.5	140	43.2	11.2	3.9	3.3	48
0.7% Carbon Normalized	140	62.5	123	57.1	12.5	4.5	3.3	48
1045	595	20.7	470	3.9	1.9	2.1	3.3	64

*The threshold stress intensity factor $\Delta K_{th} \approx 3.3\ MN/m^2\sqrt{m}$

TABLE 9 THE RELATIONSHIP BETWEEN CRITICAL CRACK SIZE AND PLASTIC ZONE SIZE - TITANIUM ALLOYS

Materials	Hardness (VHN)	Contact Pressure (MN/m^2)	Fretting Fatigue Strength (MN/m^2)	Critical Crack Size (μm)	Plastic Zone Size (μm)	The Ratio of Critical Crack Size to Plastic Zone Size	$\frac{\Delta K_{th}^*}{\Delta K_o}$	Reference
Ti-6Al-4V (IMI 318)	335	62.5	139	103	13.0	7.9	5	52
Ti-2.5 Cu (IMI 330)	228	62.5	124	129	13.6	9.5	5	52
Pure Ti (IMI 130)	265	62.5	124	129	13.3	9.7	5	52
Ti-6Al-4V	320	20.7	157	103	12.3	8.4	5	29
Ti-4Al-4Mn (RC 130 B)	354	104.0	248	32	12.3	2.6	5	23

*The threshold stress intensity factor $\Delta K_{th} \approx 5\ MN/m^2 \sqrt{m}$

TABLE 10 THE MECHANICAL PROPERTIES OF TEST MATERIALS

Label	Specimen Materials	Specimen Hardness (VHN)	Pad Materials	Pad Hardness (VHN)
UIS 01, UIS 02, UIS 03 UIS 04, UIS 05, UIS 06	4340 Steel	200	4340 Steel	213
GMS 07, GMS 08, GMS 09	1020 Carburized Steel	870	1020 Carburized Steel	607
GMS 10, GMS 11, GMS 12	1020 Carburized Steel with Electroless Nickel Plating	717	1020 Carburized Steel	576
GMS 13, GMS 14, GMS 15	1020 Carburized Steel Luburized with Phosphate Coating	798	1020 Carburized Steel Luburized with Phosphate Coating	565
UIS 16, UIS 17, UIS 18 UIS 19, UIS 20, UIS 21	4340 Steel	240	4340 Steel	232

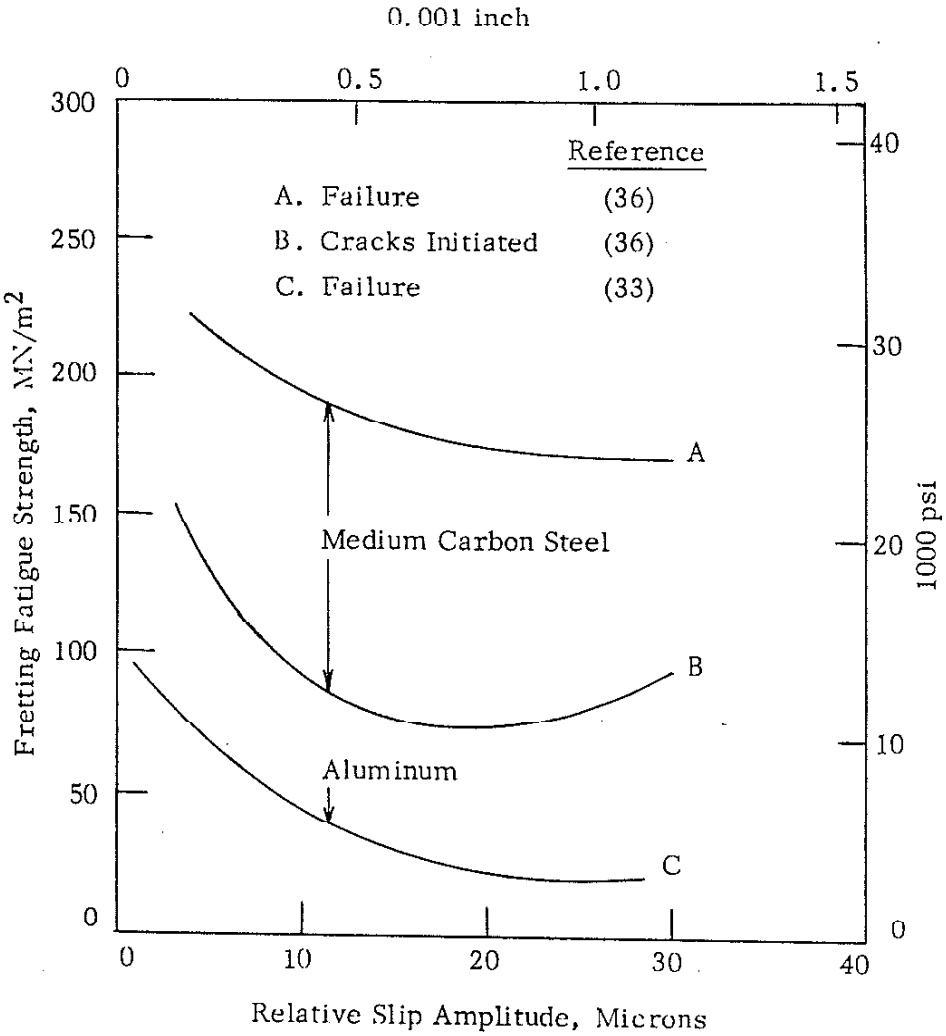


Fig. 1 Effect of Relative Slip Amplitude on Fretting Fatigue Strength

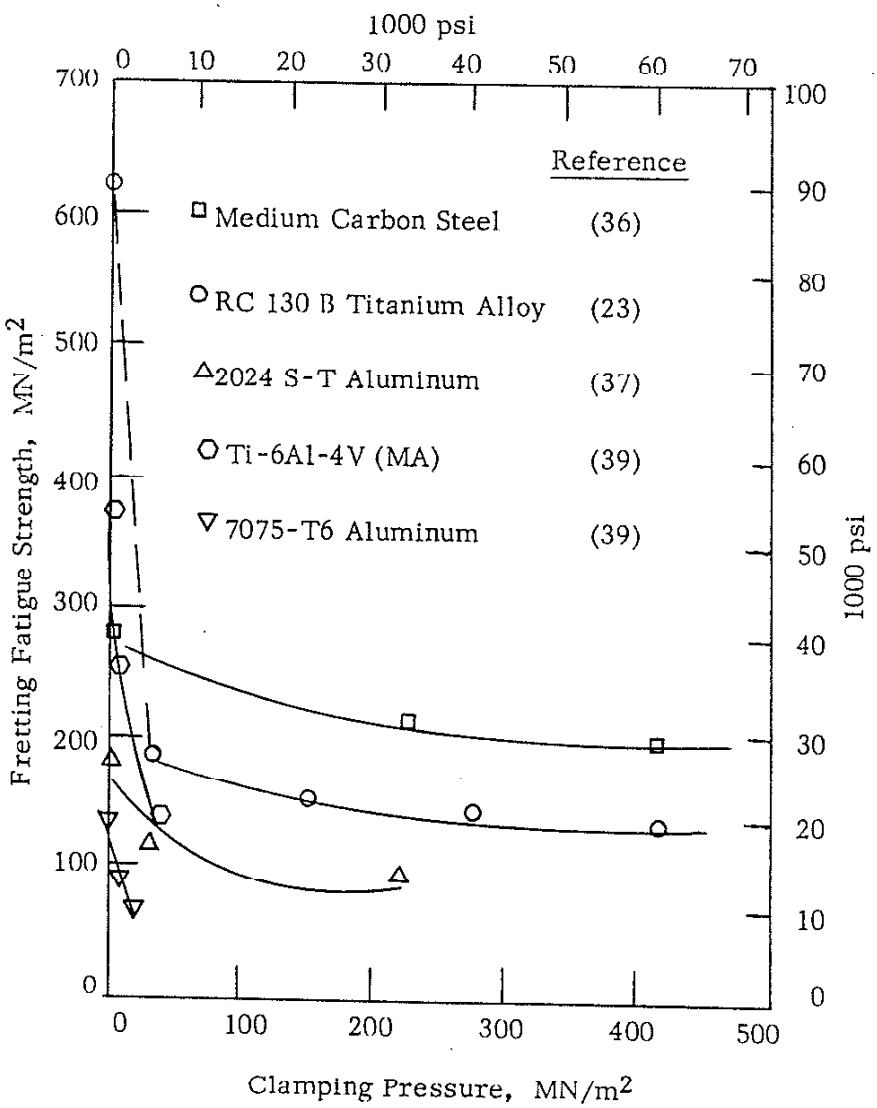


Fig. 2 Effect of Clamping Pressure on Fretting Fatigue Strength

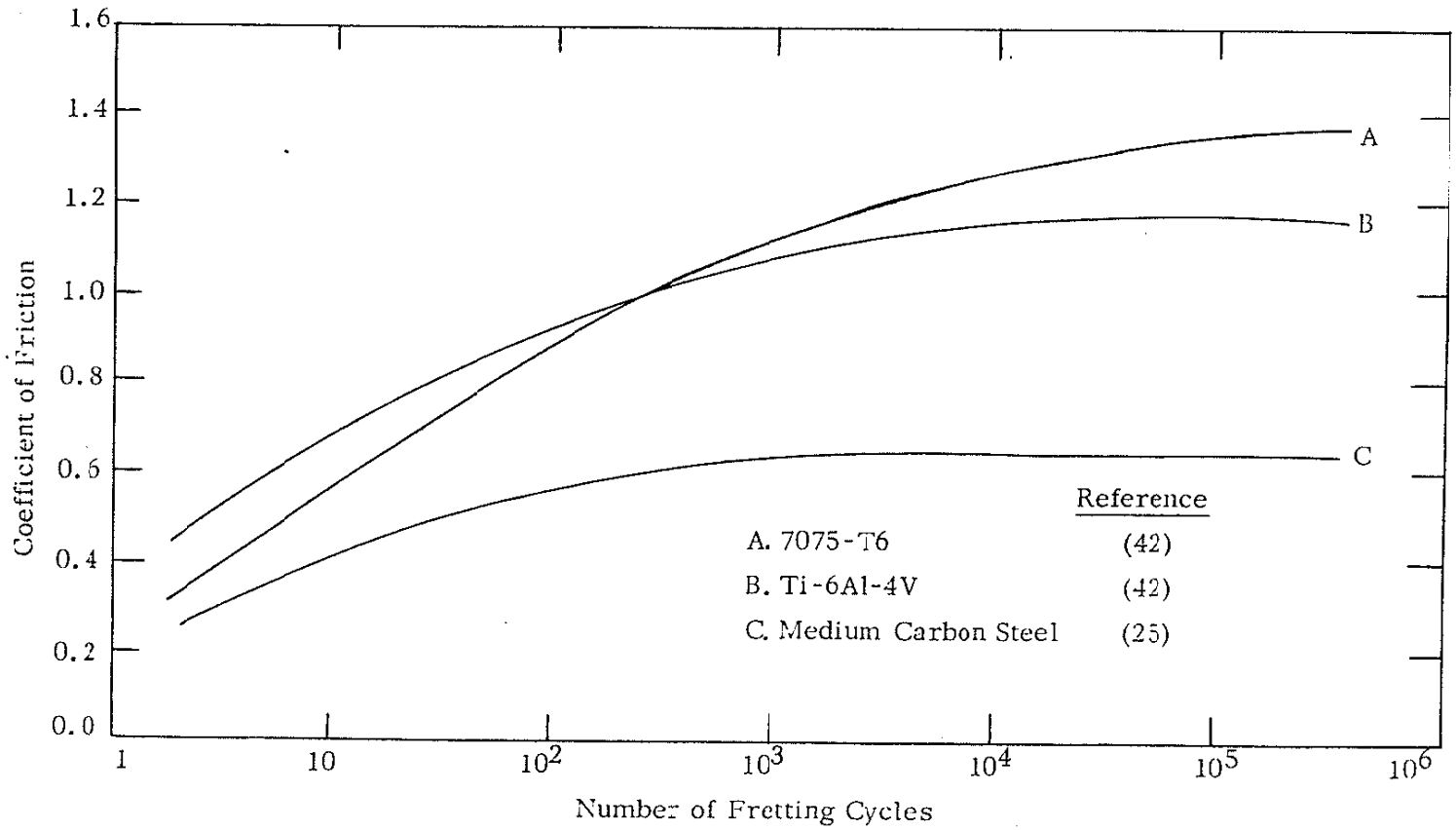


Fig. 3 Coefficient of Friction Versus Number of Fretting Cycles

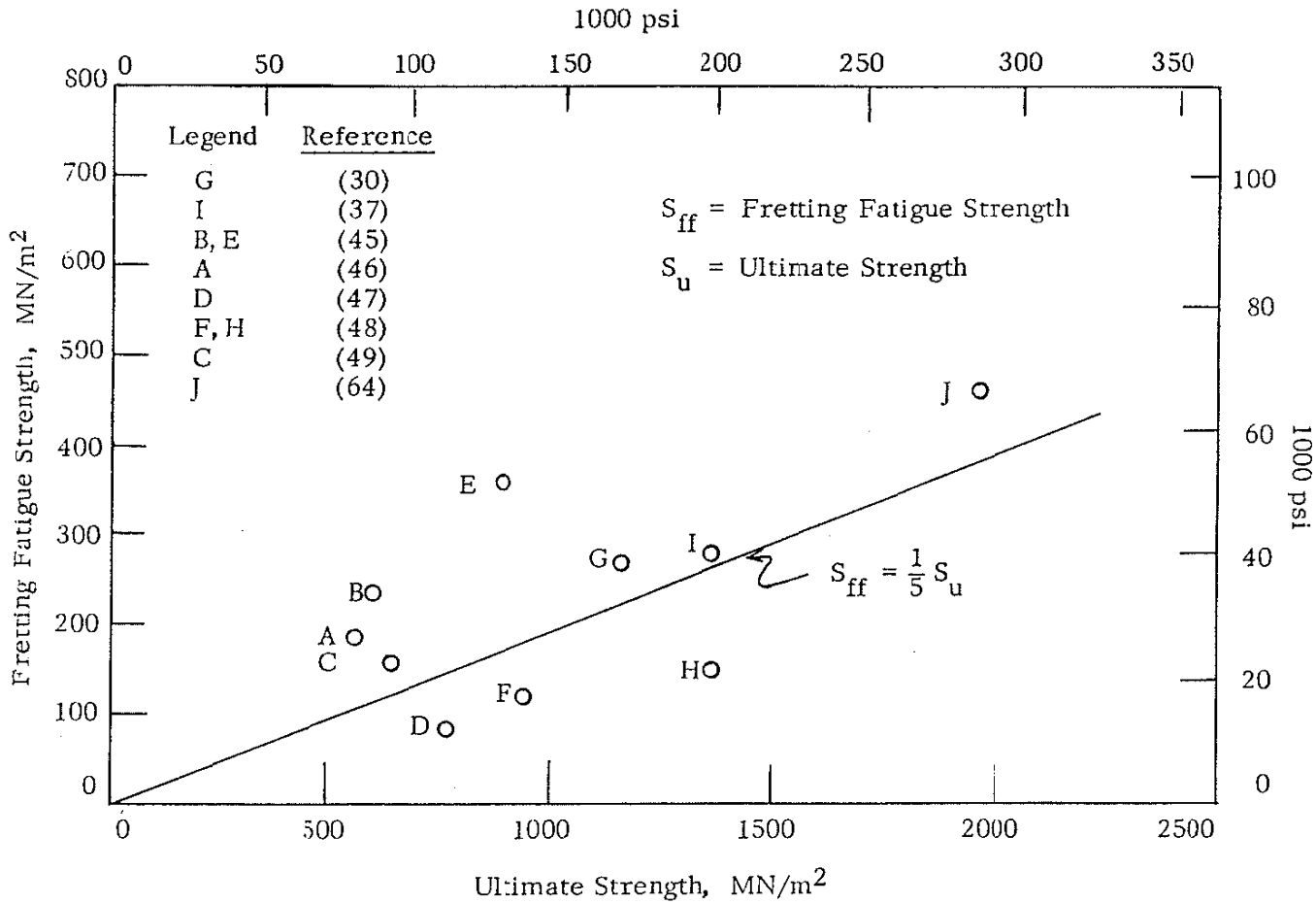


Fig. 4 The Relationship between Fretting Fatigue Strength and Ultimate Strength

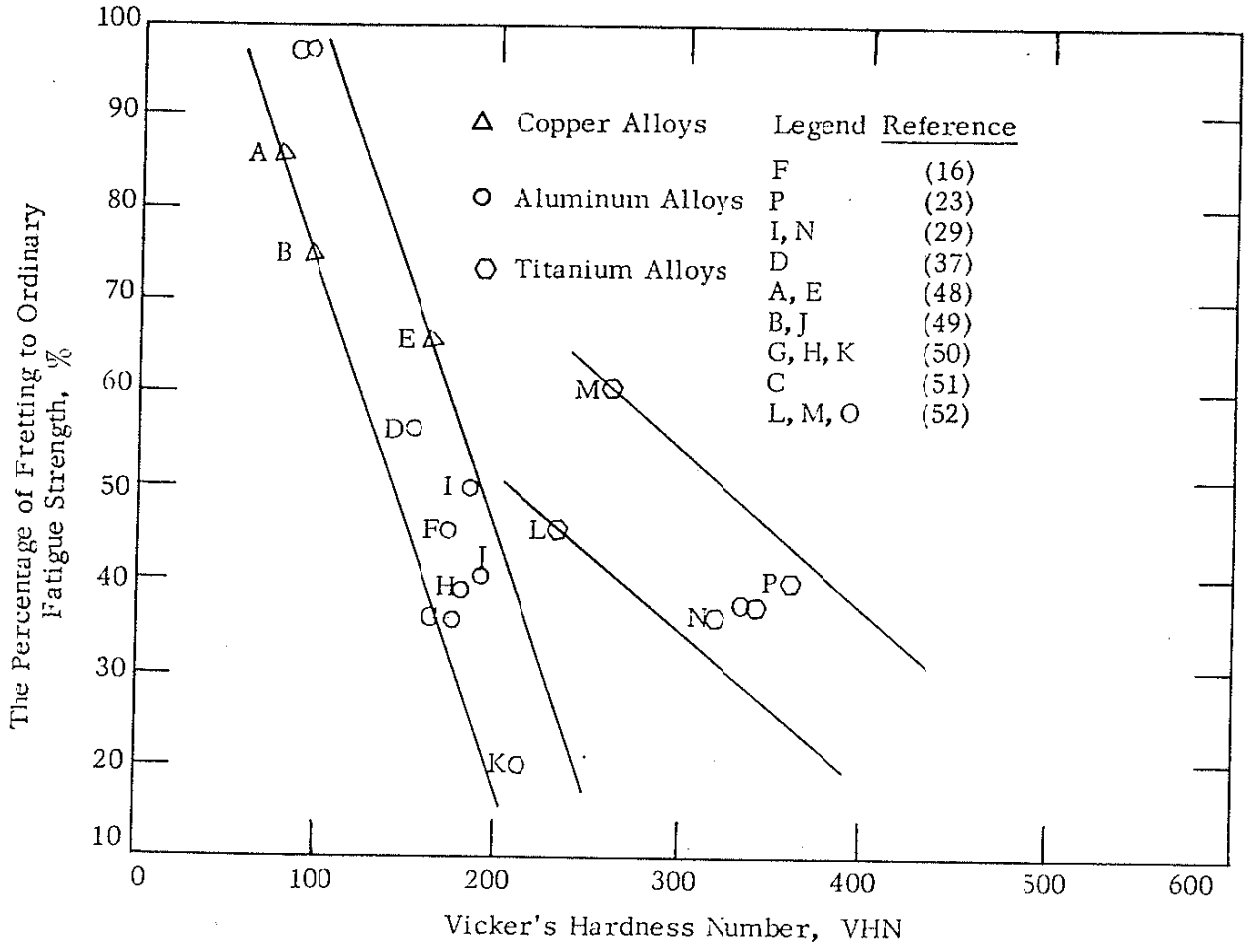


Fig. 5 The Effect of Hardness of Contacting Materials on Fretting Fatigue Strength

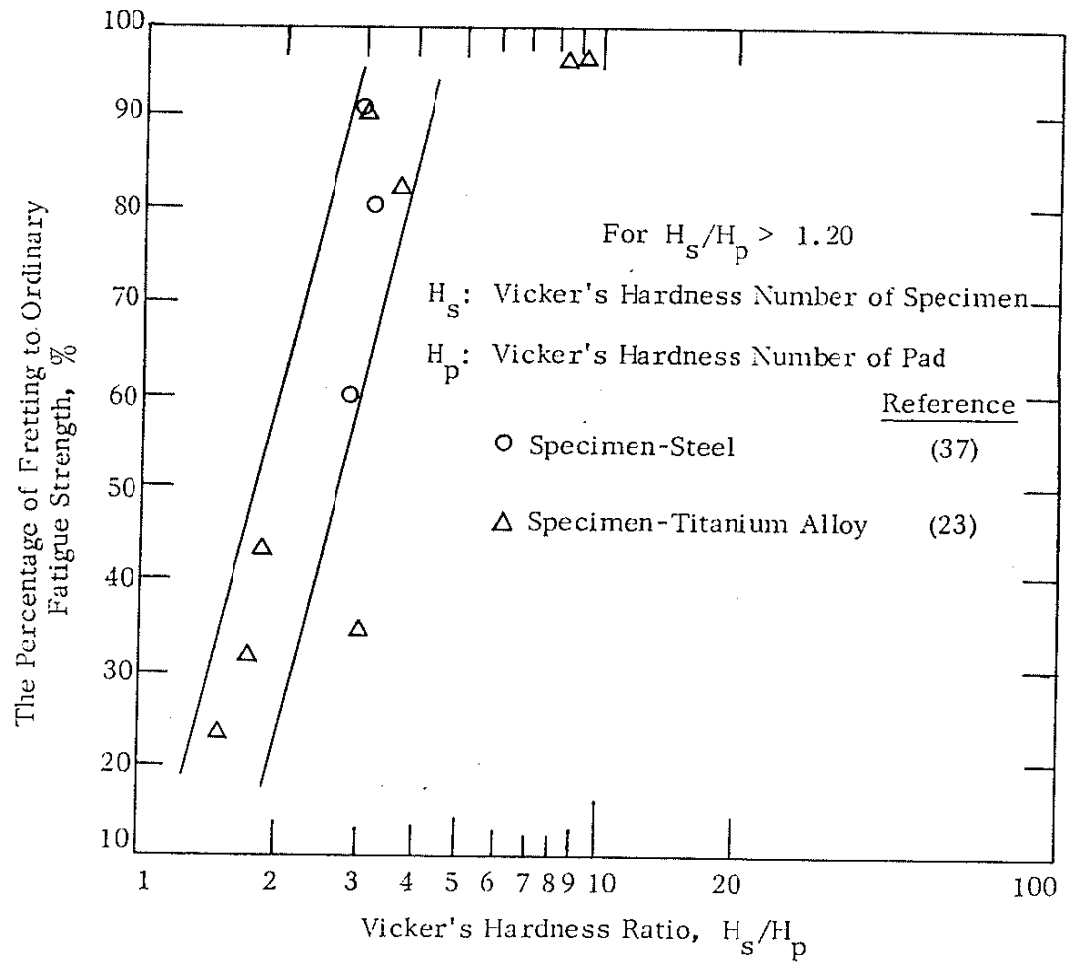


Fig. 6 The Effect of Material Combination on Fretting Fatigue Strength - Specimens Harder than Pads

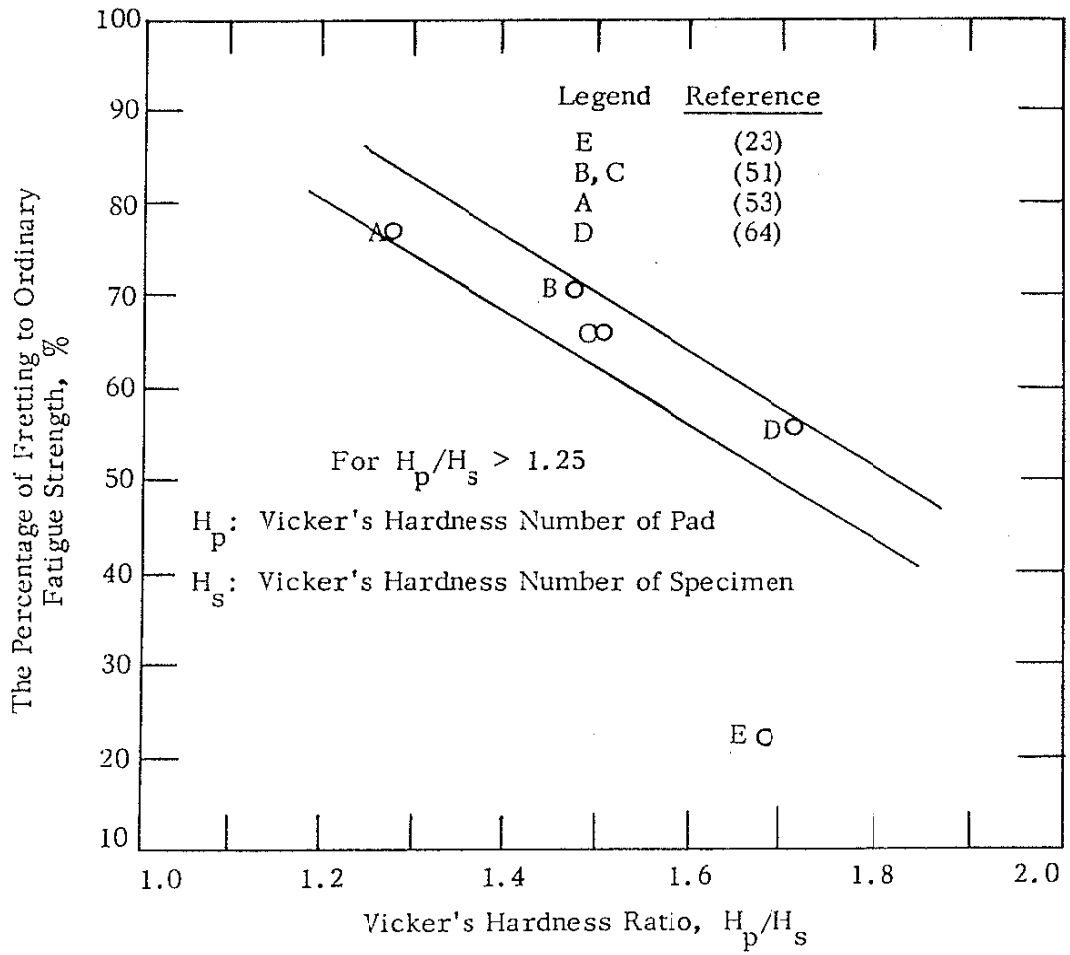


Fig. 7 The Effect of Material Combination on Fretting Fatigue Strength - Pads Harder than Specimens

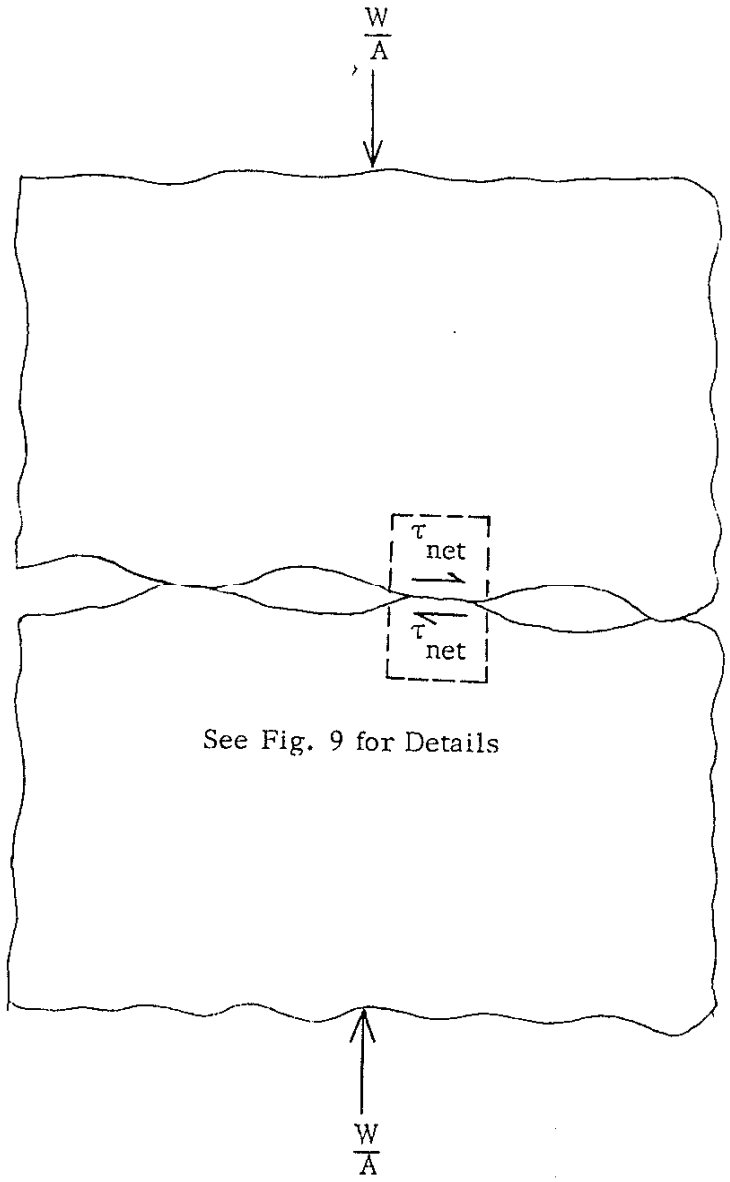


Fig. 8 Two Surfaces in Contact Subjected to Normal Force and Frictional Force

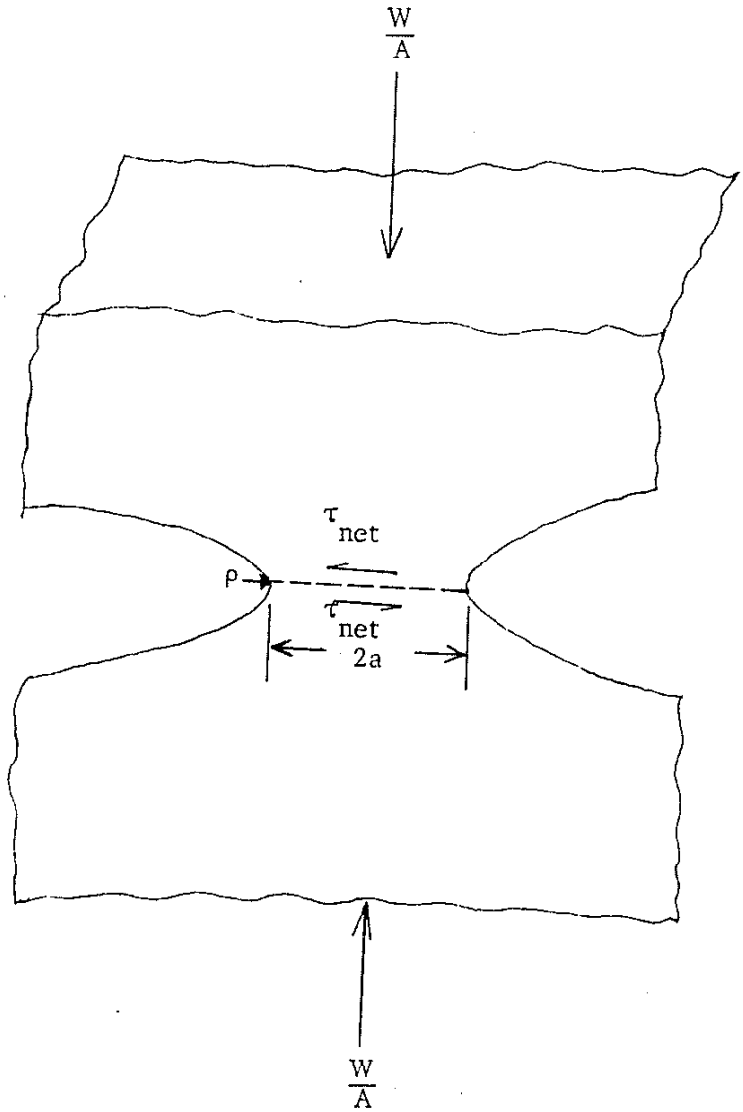
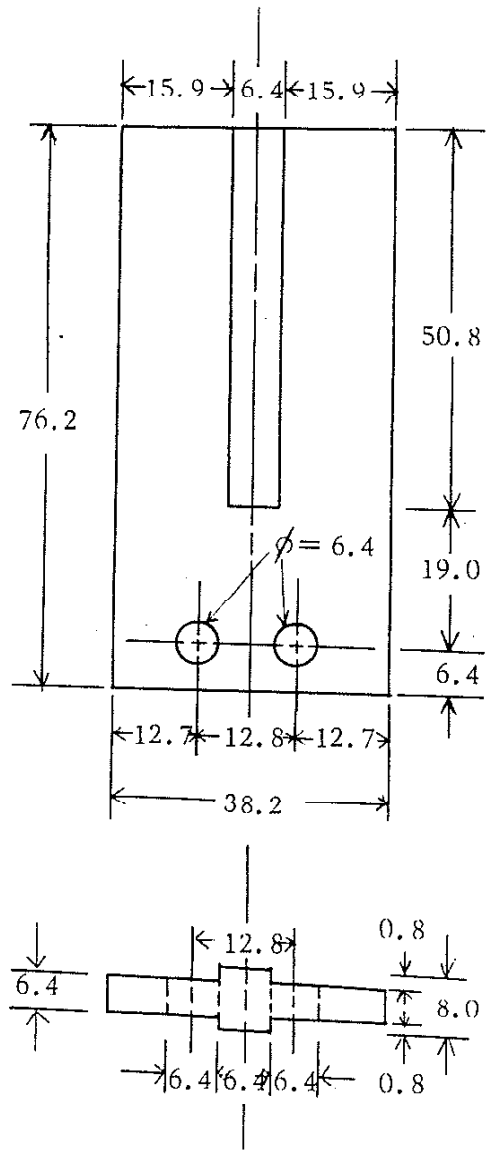
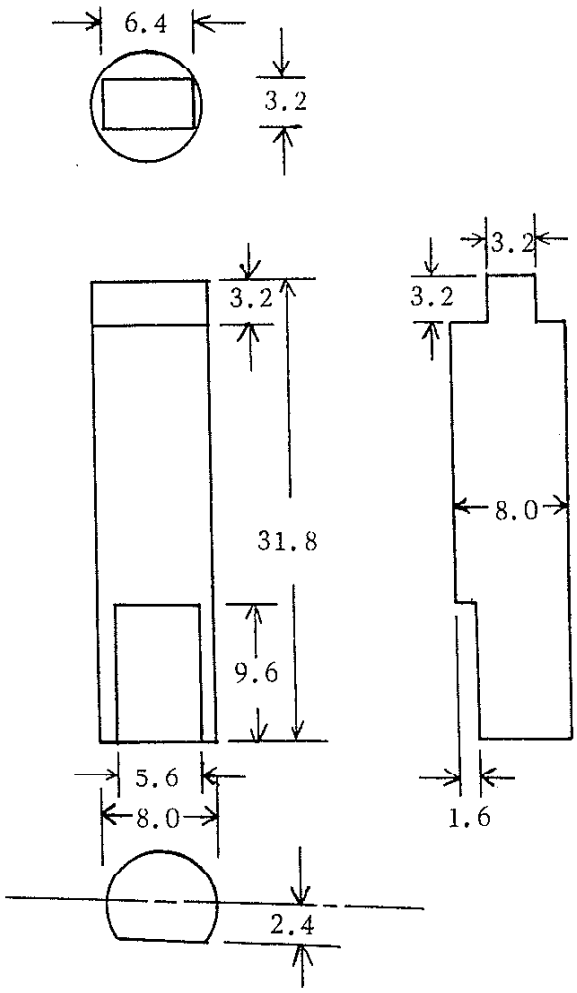


Fig. 9 Stress Field around Tips of Contacting Asperities



Unit: mm

Fig. 10 Dimensions of Specimen



Unit: mm

Fig. 11 Dimensions of Pad

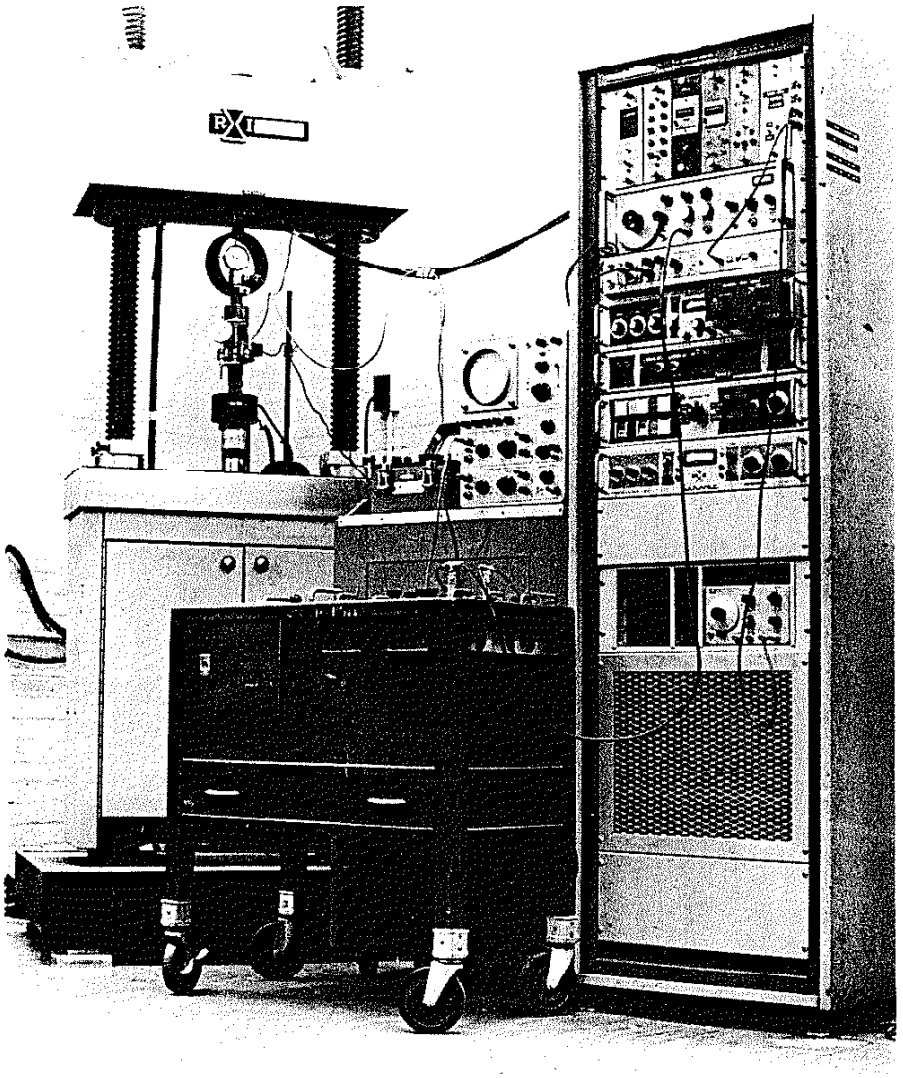


Fig. 12 Over All View of Experimental Set Up

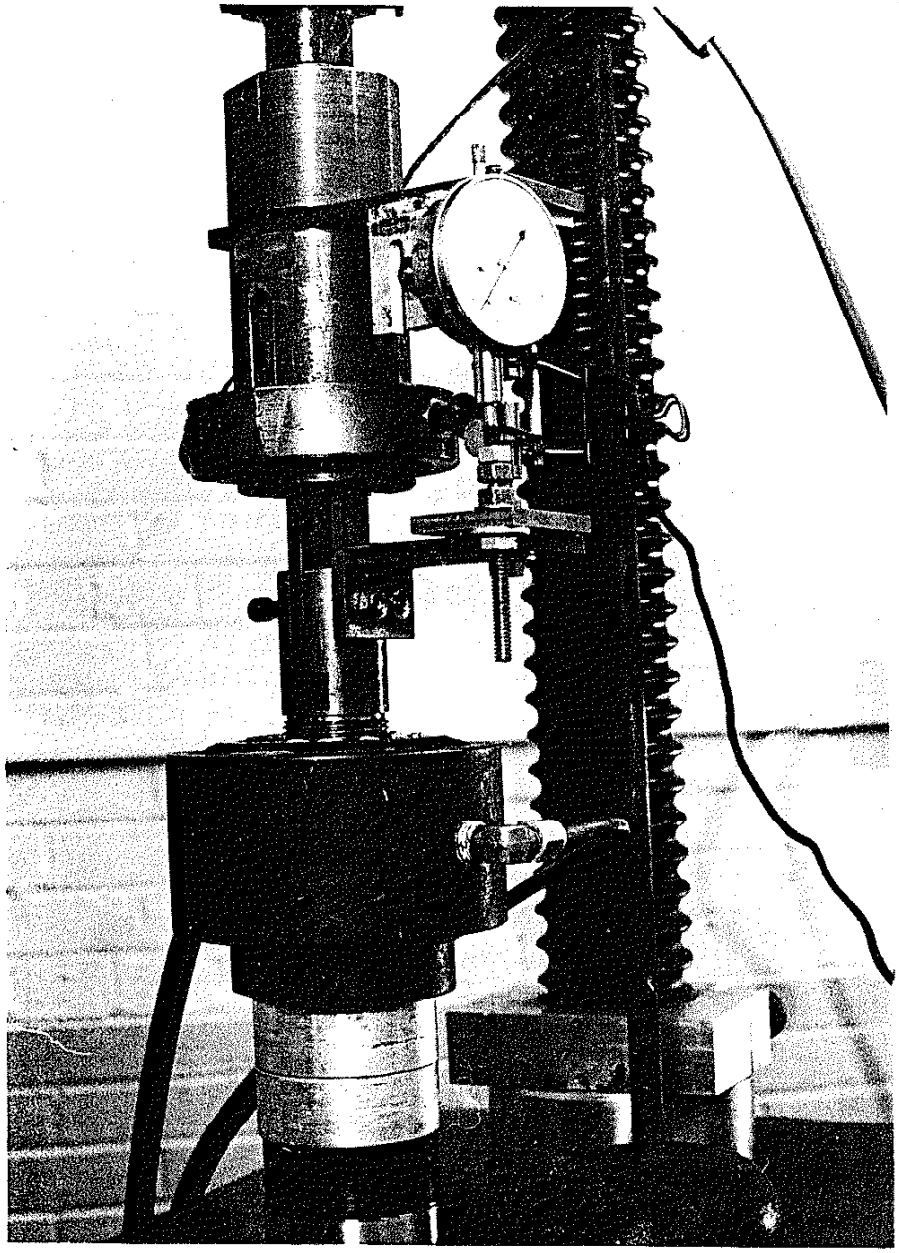


Fig. 13 Close Up View of Specimen Mounting

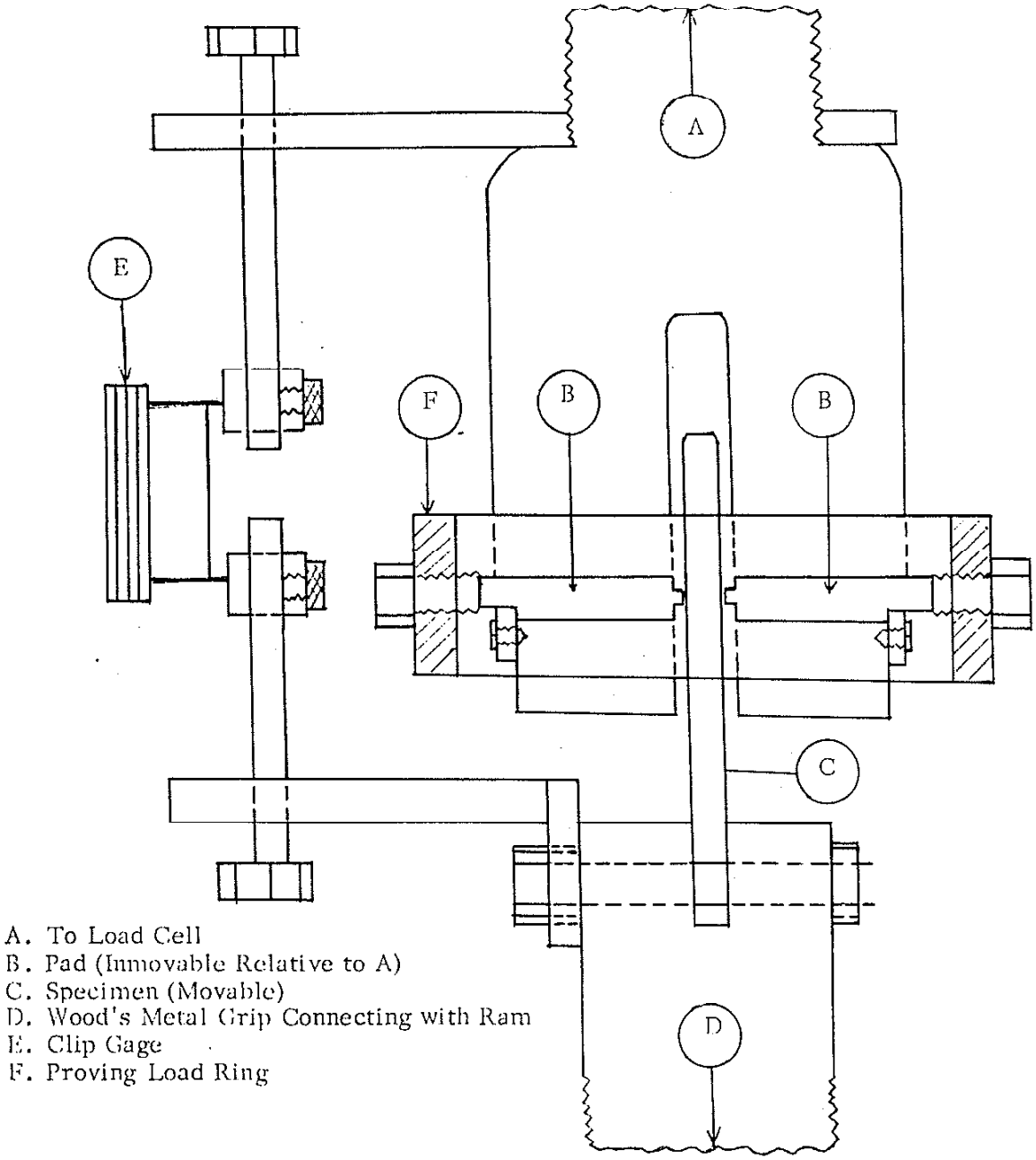


Fig. 14 Schematic Diagram of Experimental Set Up

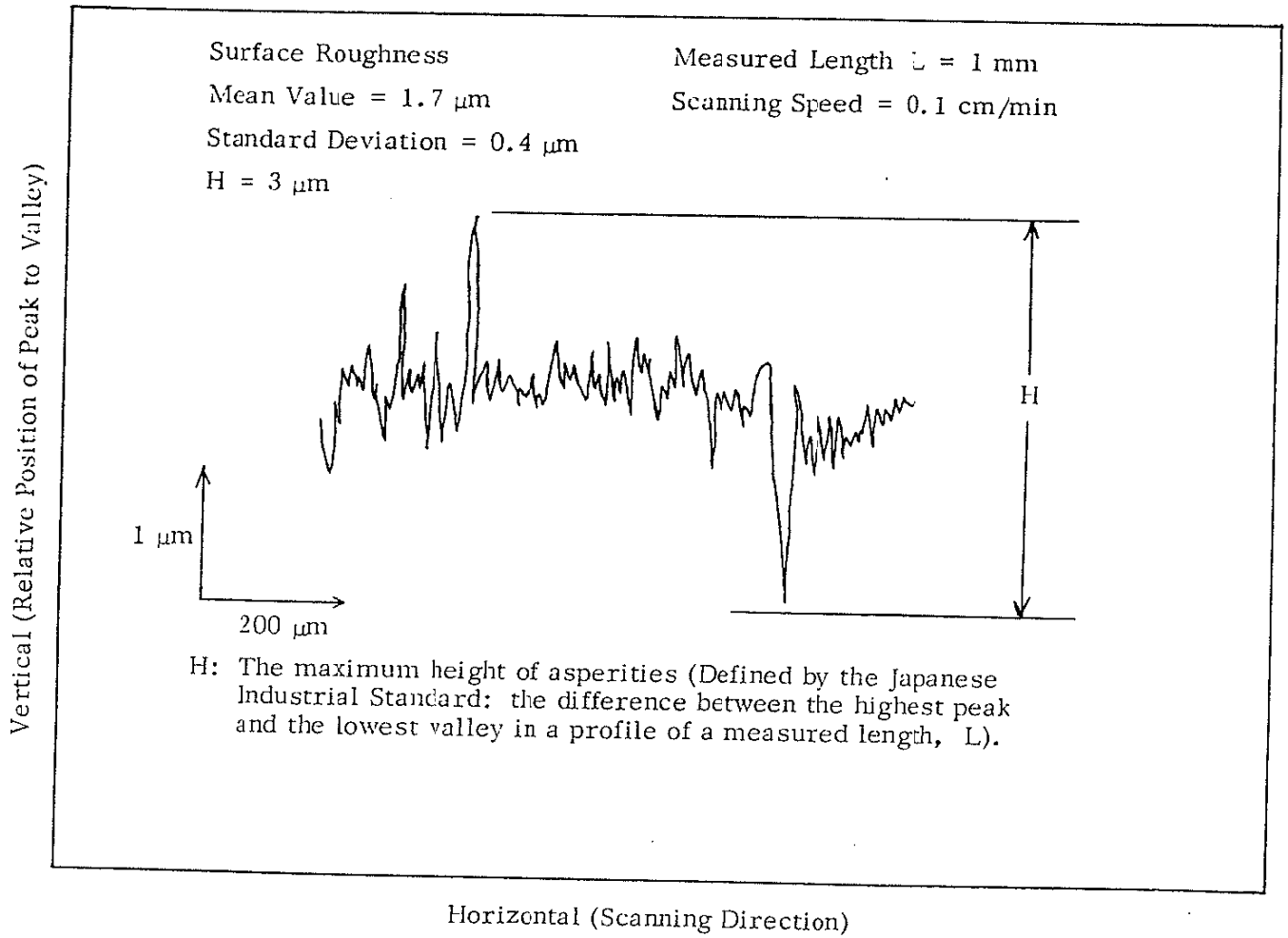


Fig. 15 Surface Profile of Specimen

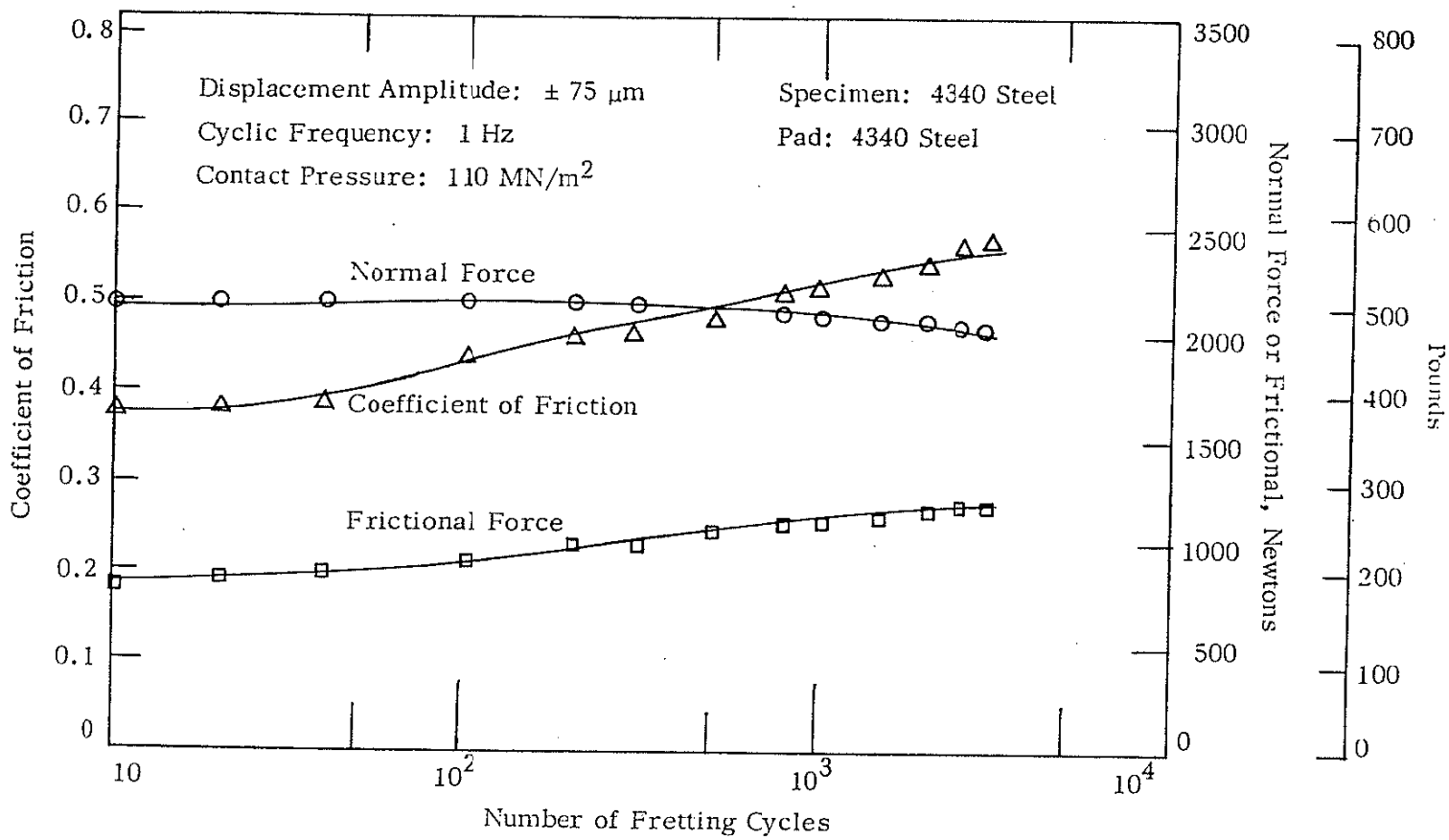


Fig. 16 Typical Experimental Results of Fretting Study

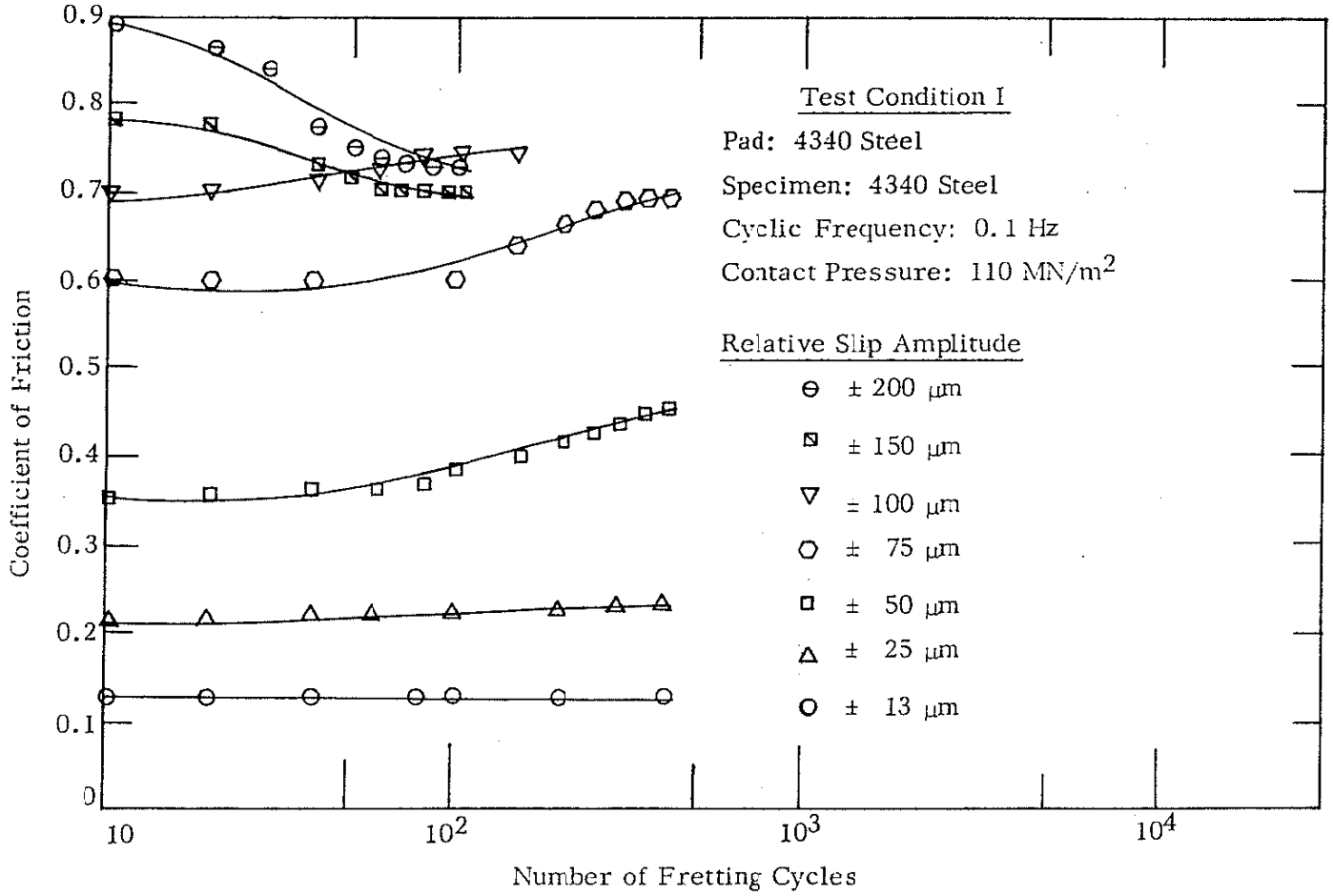


Fig. 17 The Effect of Relative Slip Amplitude on Coefficient of Friction - Test Condition I

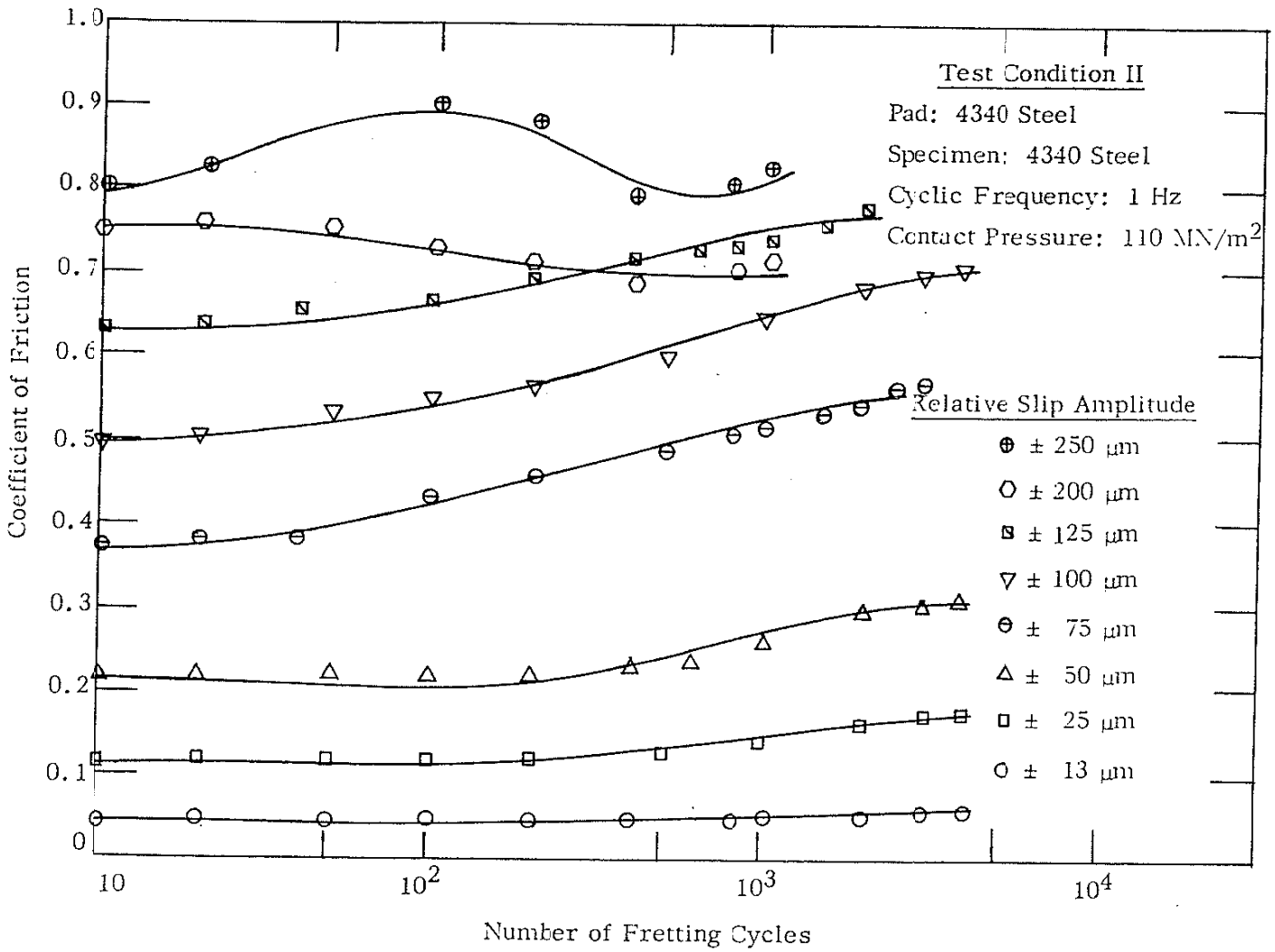


Fig. 18 The Effect of Relative Slip Amplitude on Coefficient of Friction - Test Condition II

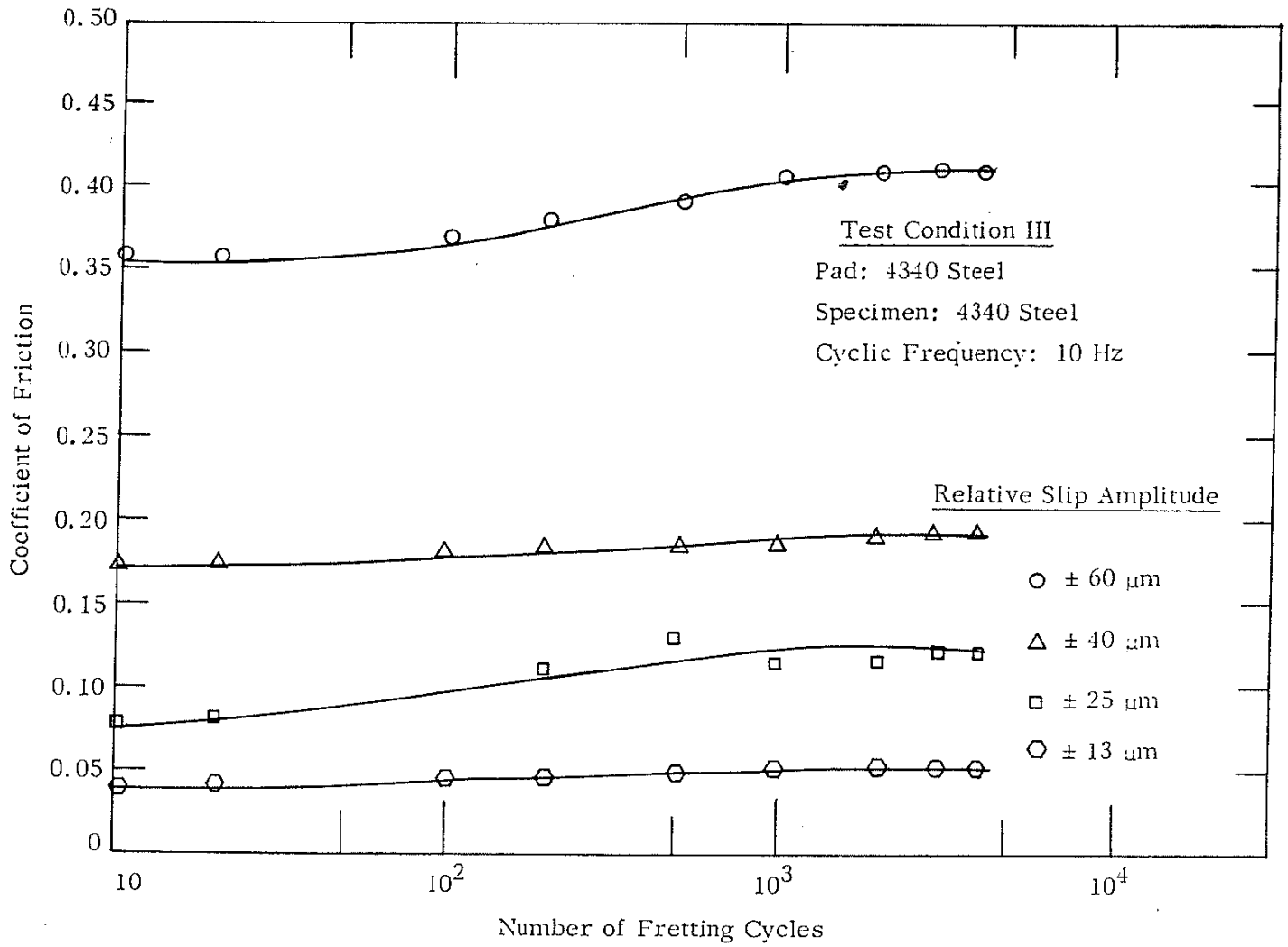


Fig. 19 The Effect of Relative Slip Amplitude on Coefficient of Friction - Test Condition III

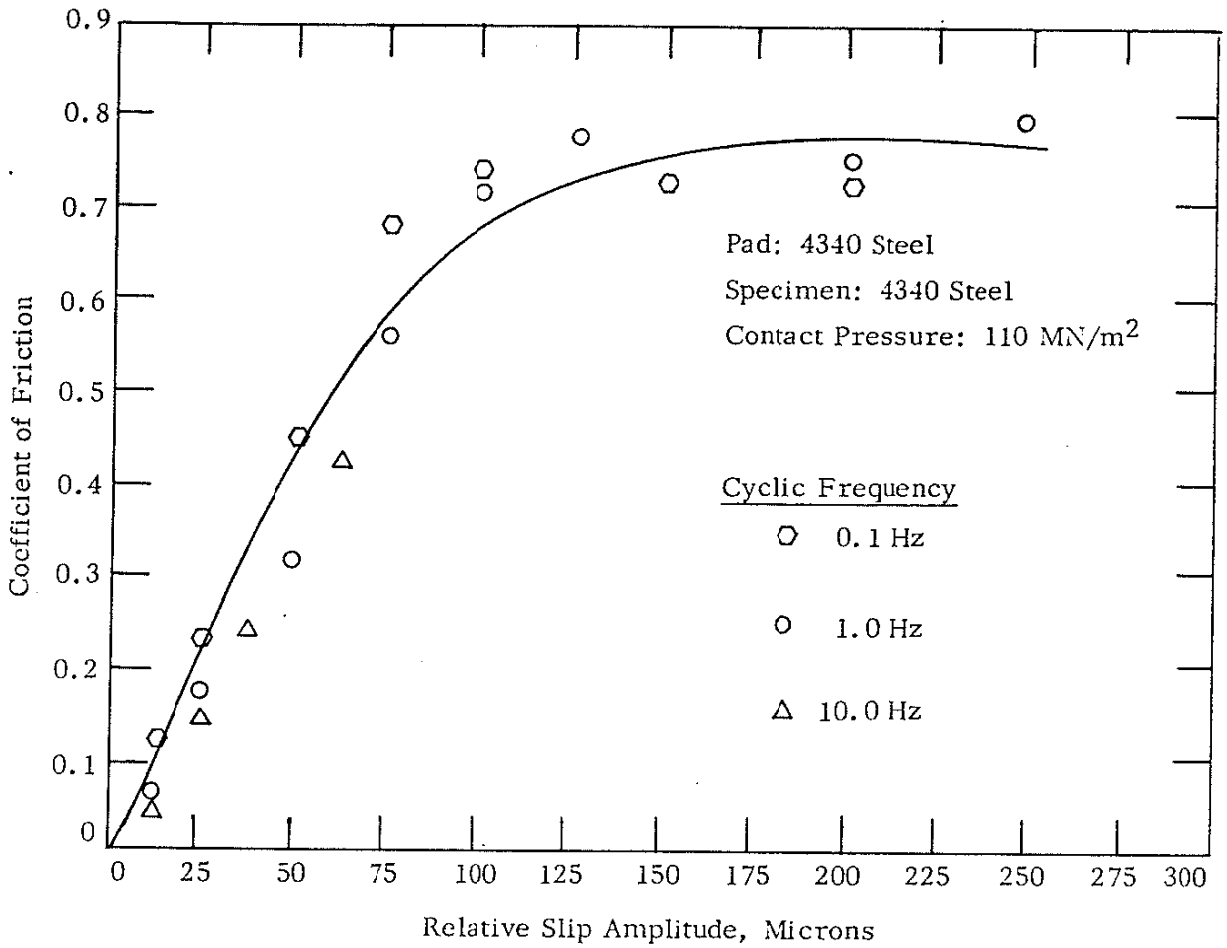


Fig. 20 The Effect of Relative Slip Amplitude on Coefficient on Friction - Saturation Values

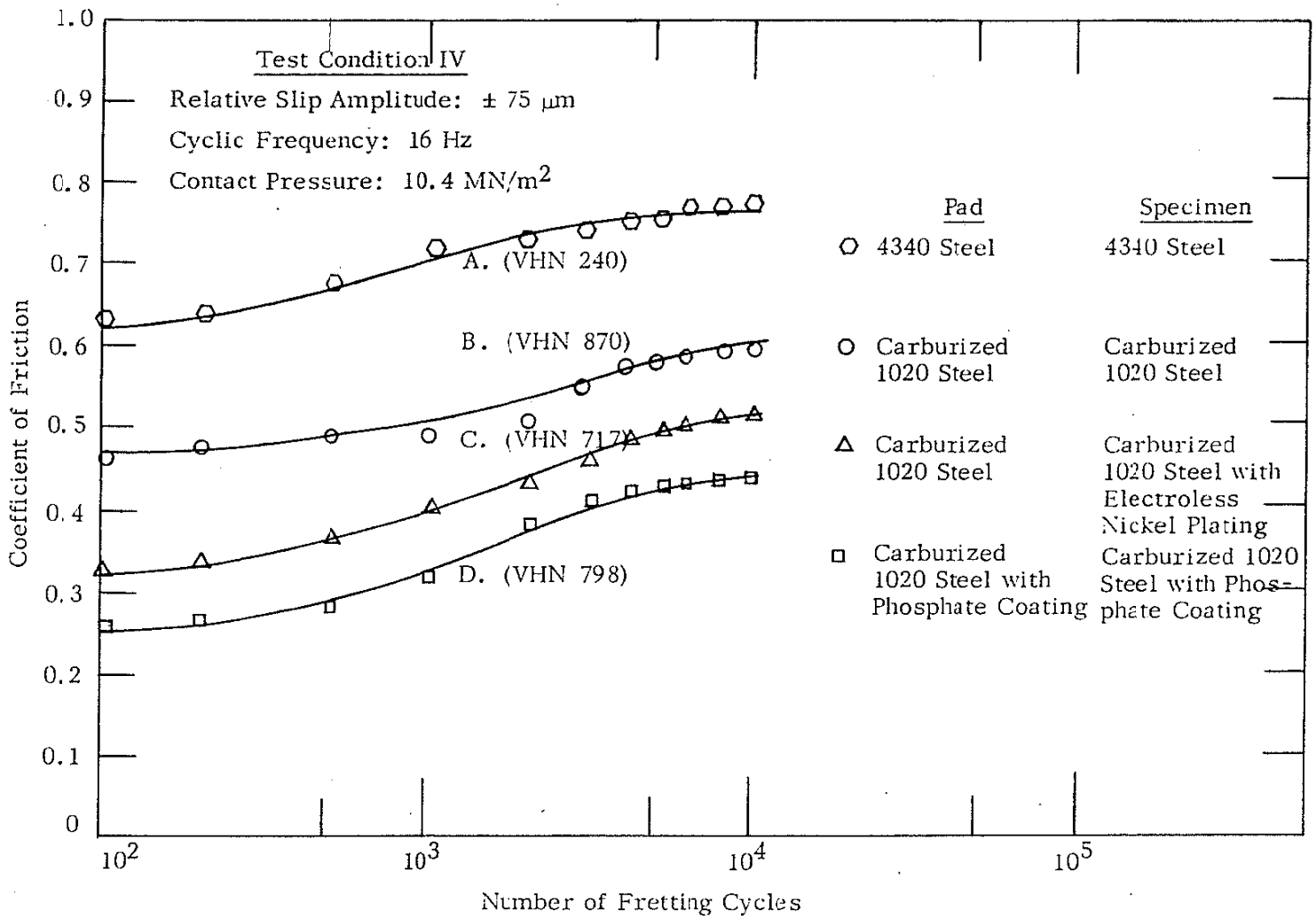


Fig. 21 The Effect of Contacting Material on Coefficient of Friction - Test Condition IV

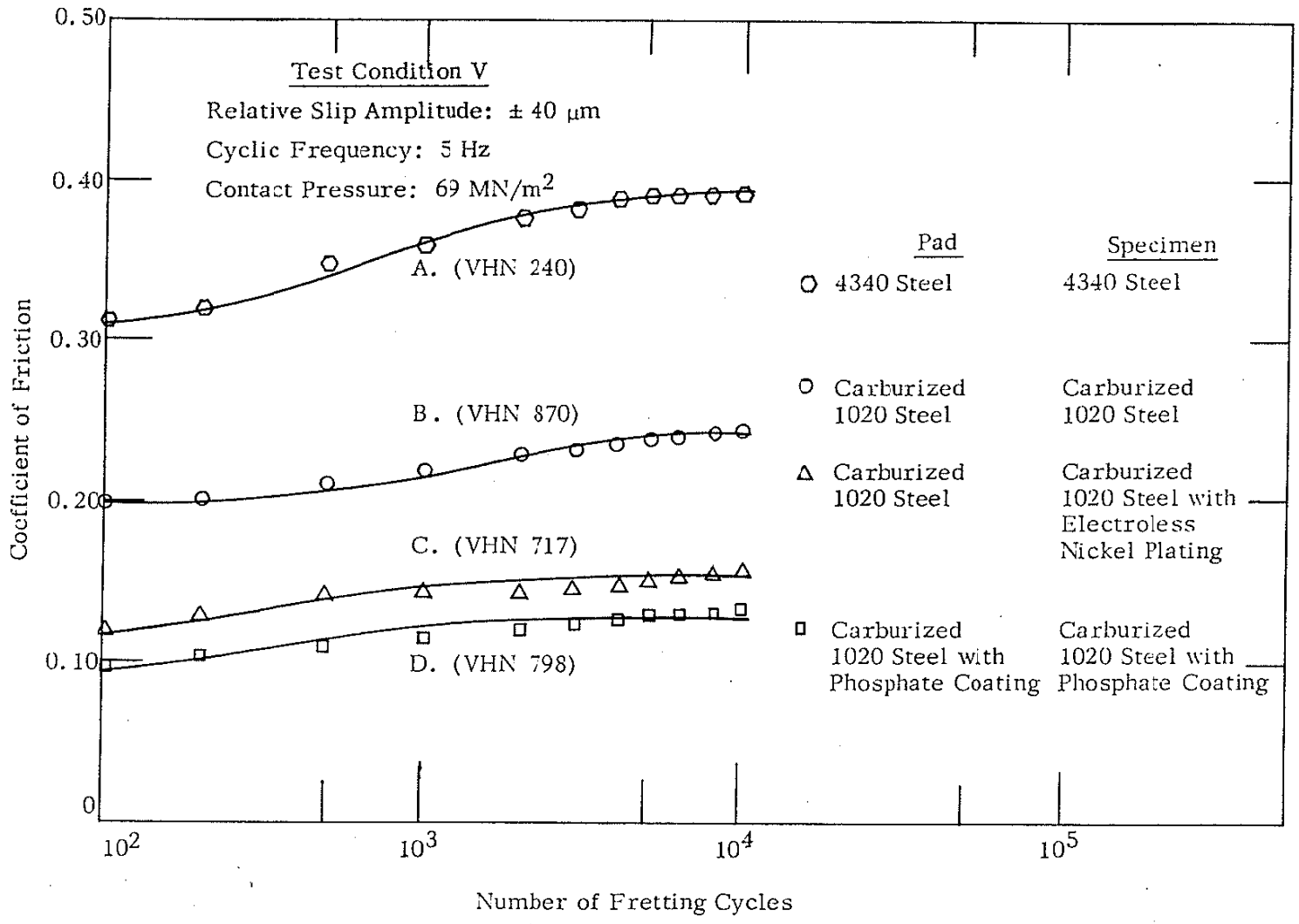


Fig. 22 The Effect of Contacting Material on Coefficient of Friction - Test Condition V

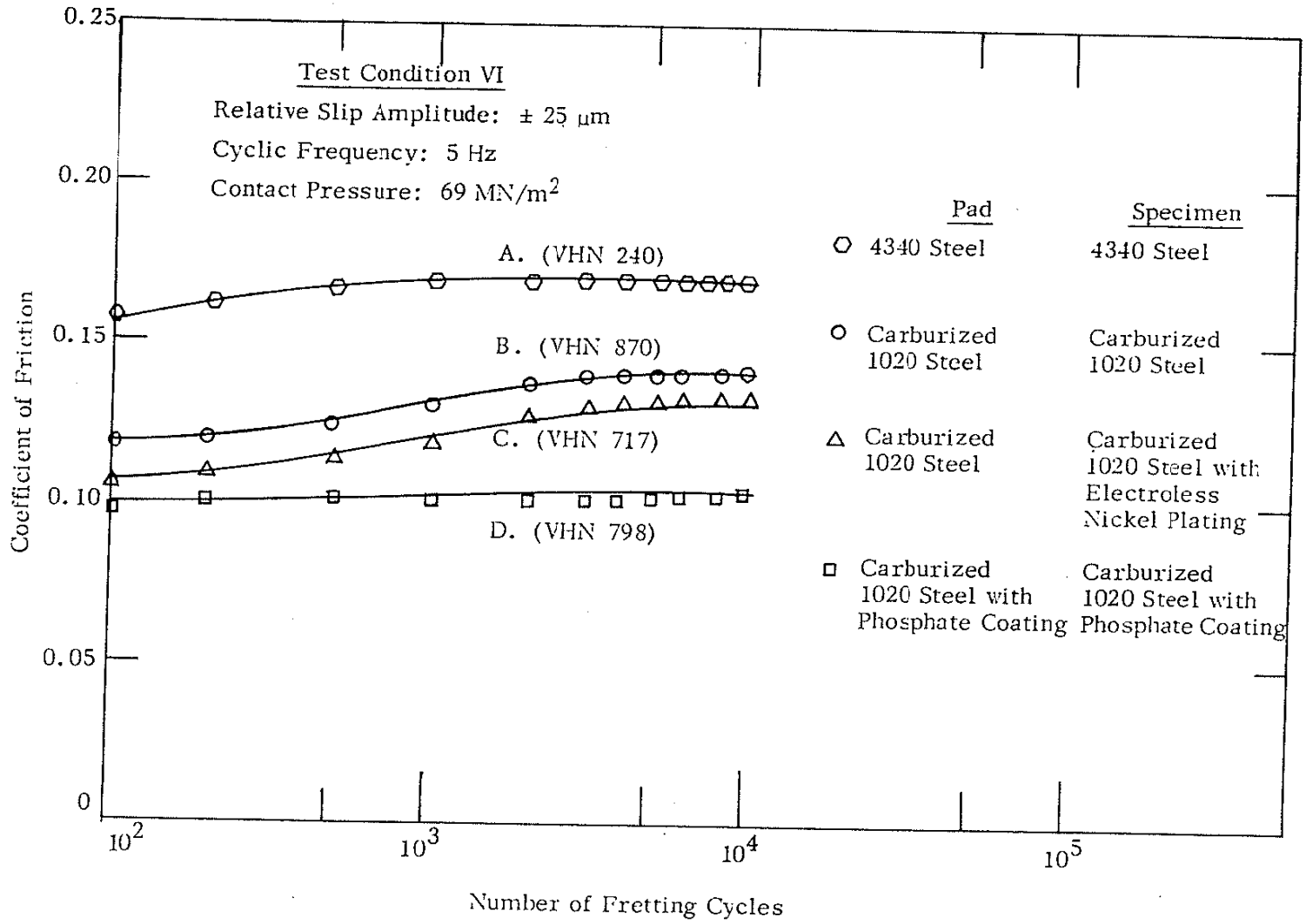


Fig. 23 The Effect of Contacting Material on Coefficient of Friction - Test Condition VI

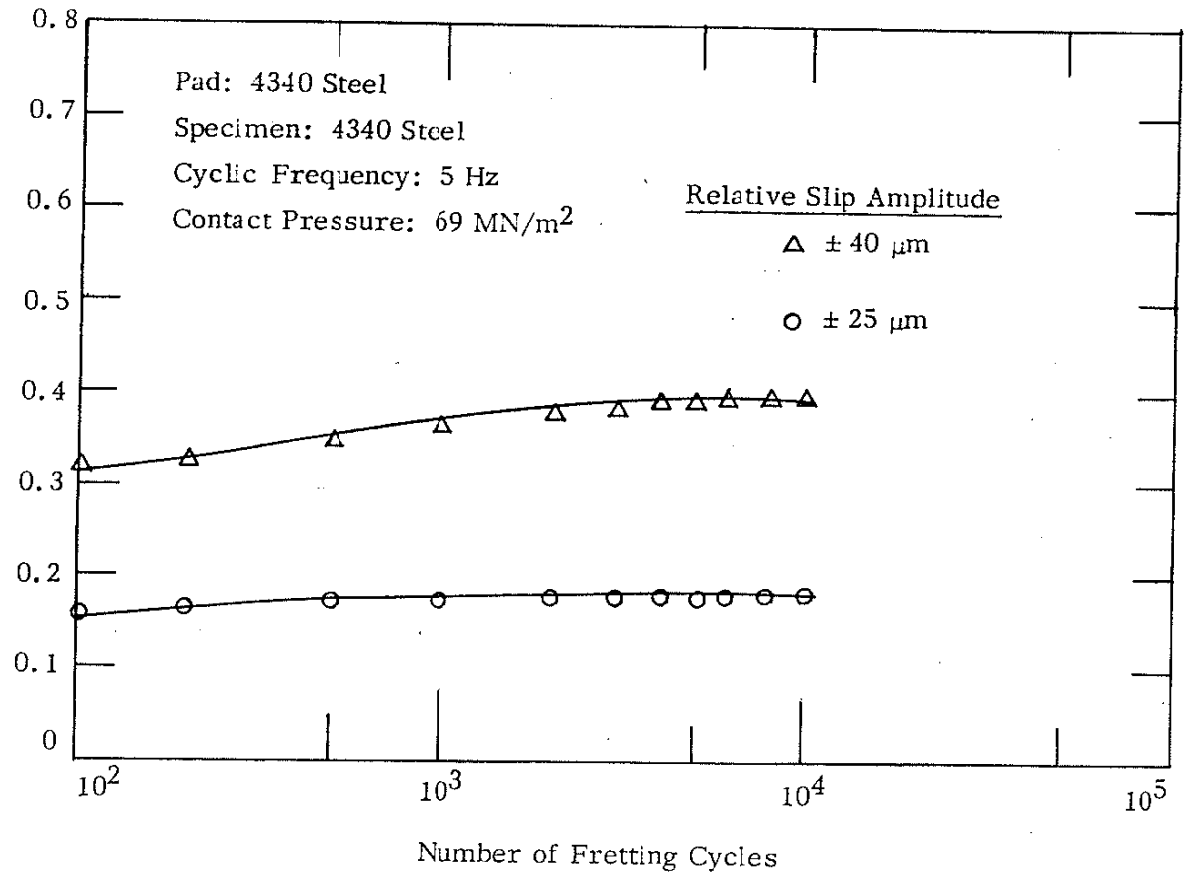


Fig. 24 The Effect of Relative Slip Amplitude on Coefficient of Friction - Steel against Steel

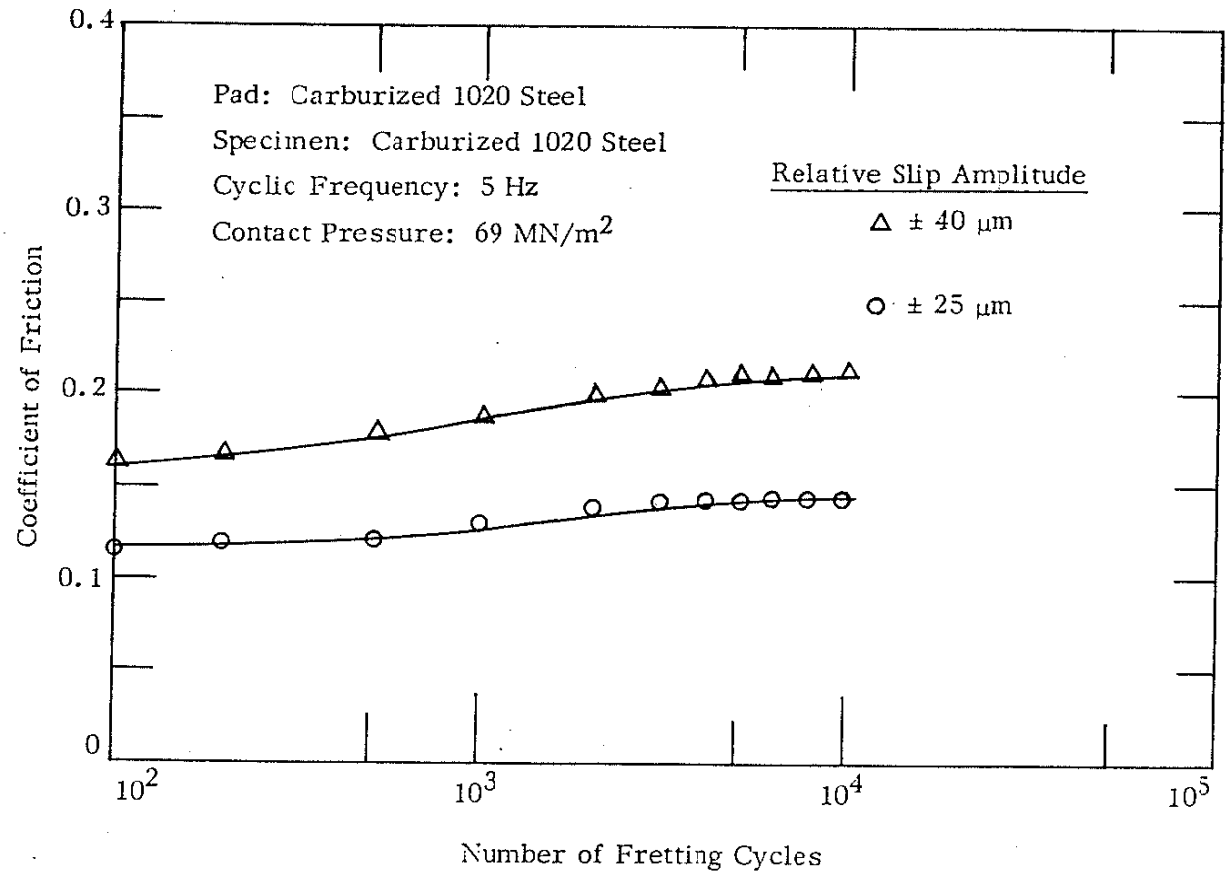


Fig. 25 The Effect of Relative Slip Amplitude on Coefficient of Friction - Carburized Steel against Carburized Steel

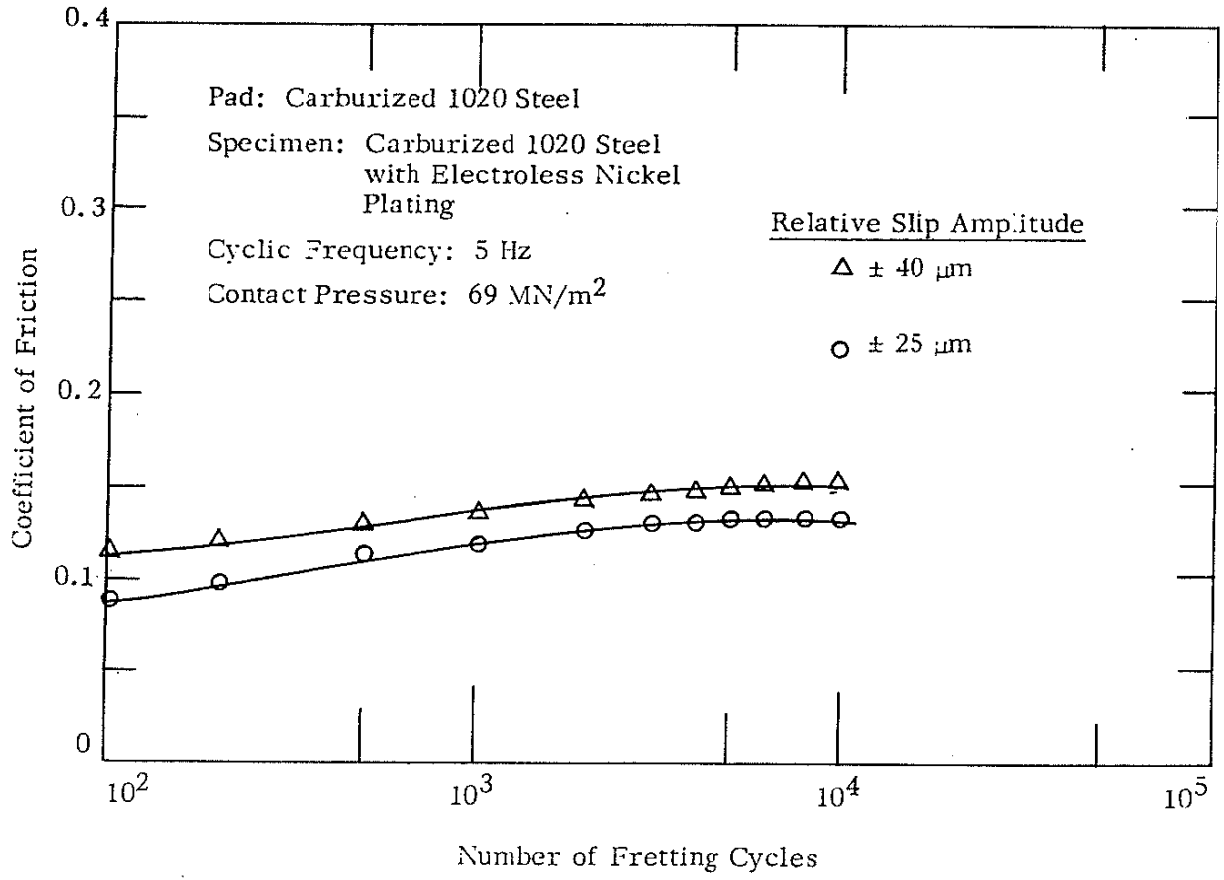


Fig. 26 The Effect of Relative Slip Amplitude on Coefficient of Friction - Carburized Steel against Carburized Steel with Electroless Nickel Plating

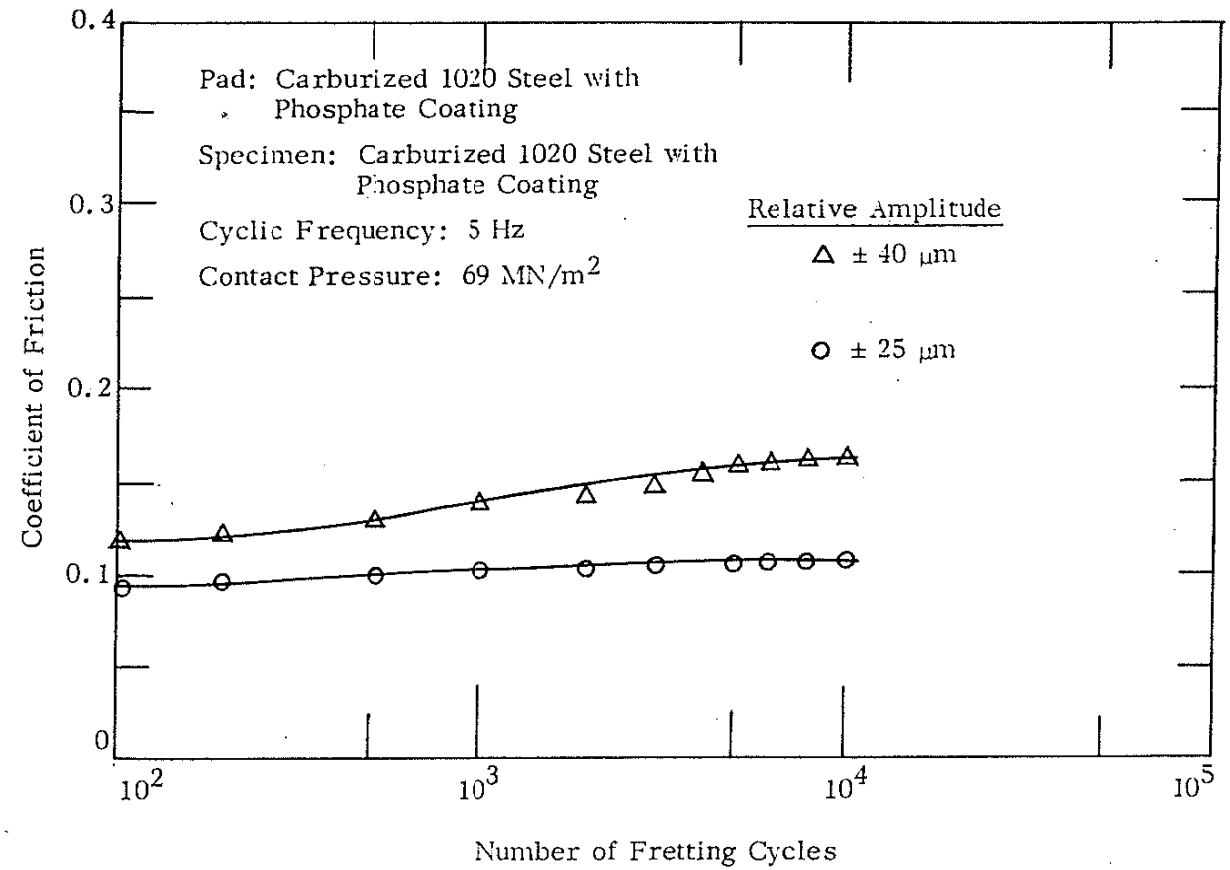


Fig. 27 The Effect of Relative Slip Amplitude on Coefficient of Friction - Carburized Steel with Phosphate Coating against Carburized Steel with Phosphate Coating

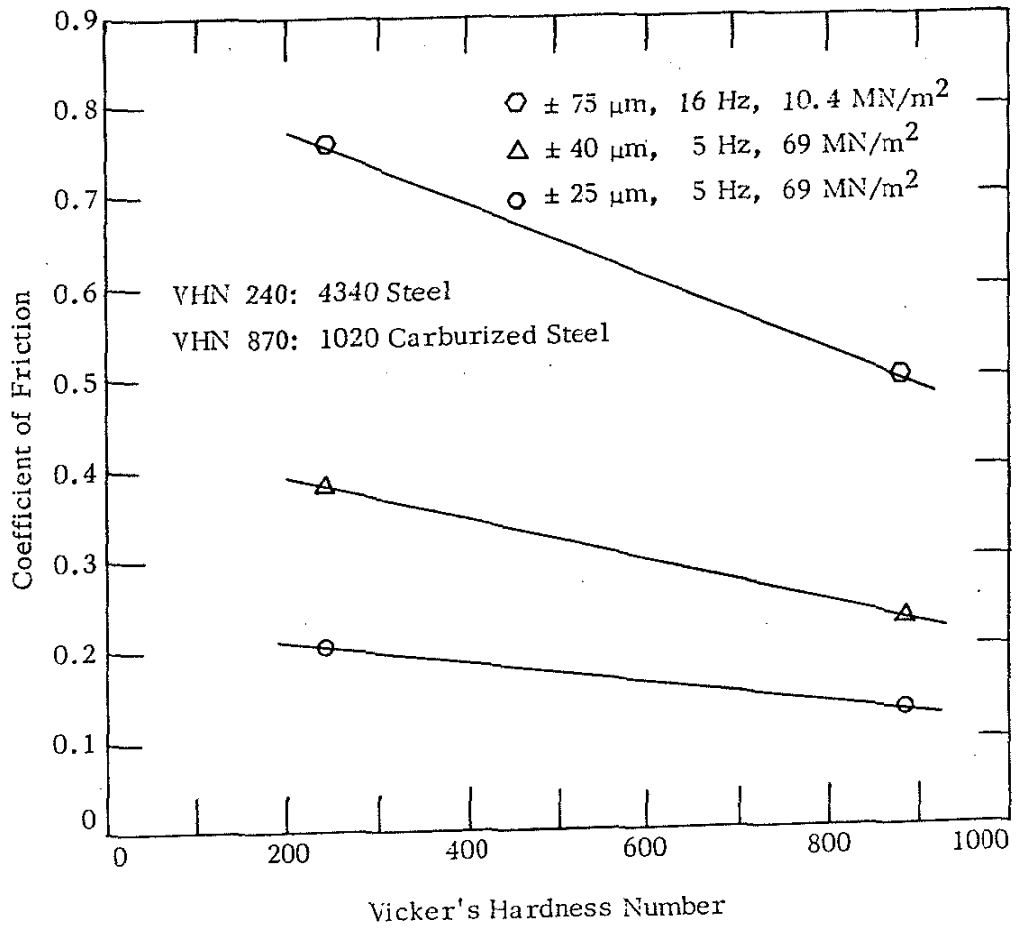


Fig. 28 The Effect of Test Condition on Coefficient of Friction of Same Material Combination