EFFECTS OF POLISHED ROD CLAMPS ON POLISHED ROD FATIGUE LIFE

Larry Angelo
J. M. Huber Corporation
Flow Control Division

Introduction

Most polished rods break at the bottom of the polished rod clamp. Almost all of these breaks are fatigue failures. A study of polished rod fatigue failures entitled *How to Minimize Polished Rod Breaks* (Ref. 1) was presented at the 41st Annual Southwestern Petroleum Short Course in April, 1994. The study concluded that bending stresses amplified by stress concentrations from polished rod clamps are the most significant contributors to polished rod fatigue failures. The study also pointed out a noticeable absence of information on stress concentrations caused by various polished rod clamps.

This paper picks up where the above study left off. Recent experimental results are reported on the effects of stress concentrations generated by polished rod clamps on the fatigue strength of polished rods. The major objective of the investigation was to determine and to compare polished rod endurance limits resulting from indention and friction style clamps. This objective was achieved by conducting fatigue tests on polished rods using both clamp designs. Test results are presented in the form of stress-cycle curves which were used to determine the endurance limits for polished rods equipped with indention and friction style clamps.

Endurance Limit

Stress-cycle curves, sometimes referred to as stress-number (S-N) curves, are typically used to analyze data from fatigue tests. A typical S-N curve for a ferrous material is shown in Figure 1 (Ref. 2). As fluctuating stresses decrease, the number of stress cycles to cause failure increases. The endurance limit is that stress at which the slope of the S-N curve becomes flat or zero. If fluctuating stresses are maintained below the endurance limit of a material, a part manufactured from the material will not fail in fatigue.

Endurance limits can only be determined experimentally. Test specimens used in fatigue tests are polished to eliminate the effects of surface imperfections. Imperfections such as inclusions, small scratches and dents can generate stress concentrations that produce crack initiation sites and reduce the endurance limit. Polished rod clamps, by design, cause radial pressure, fretting, and indentions which result in stress concentrations on the surface of polished rods. These stress concentrations lower the endurance limit of the polished rod.

Polished Rod Clamp Design

Polished rod clamps can be divided into two basic designs-- indention and friction models. Huber Fig. 1, Fig. 2 and Fig. 3 clamps are indention models. A Fig. 2 indention clamp is illustrated in Figure 2(a). The I.D. of the clamp is machined smaller than the O.D. of the polished rod so that each set of lands shown in Figure 2(b) has four contact points with the polished rod. Therefore, the clamping forces are concentrated on small areas of the polished rod. Friction models distribute the forces over a larger area by machining the I.D. of the clamp equal to the O.D. of the polished rod as shown in Figure 3.

Both designs introduce stress concentrations which reduce the endurance limits of polished rods. Indention clamps support more polished rod load at lower bolt torques as shown in Figure 4 but create greater localized stress concentrations. Friction clamps require more bolt torque to support the same polished rod load but spread stress over a greater area. Therefore, in order to determine if one design had an advantage over the other, fatigue tests were conducted to determine the effect each style had on the endurance limit of a polished rod.

Experimental Method

The experimental apparatus shown in Figures 5(a) and 5(c) was used to create rotating bending stresses in a 1 1/4" diameter polished rod. The polished rod became a cantilevered beam. The free end was deflected and the opposite end with the polished rod clamp was rigidly secured. Deflection created a maximum bending stress at the intersection of the polished rod and clamp. Magnitude of the stress was varied by changing the offset in the rotating deflection plate.

For each test the clamp was assembled on the polished rod and then secured rigidly between two plates as shown in Figure 5(a). This method of holding the clamp was selected because it did not alter the radial compressive loads imposed on the polished rod by the clamp.

Maximum bending stresses were calculated for each test using cantilevered beam theory. Calculated stresses were then confirmed before each test by measuring actual stresses with a uni-axial strain gage.

Polished rod specimens were prepared from commercially available 1-1/4" AISI 1045 "piston steel" polished rods. The free end was machined to fit the spherical bearing located in the rotating deflection plate. The clamped end was used "as received" without any special surface preparation. Polished rod clamps were installed using bolt torques of 100 ft-lbs and 250 ft-lbs for indention clamps and 230 ft-lbs for the friction clamp.

Each test was run at a constant speed of approximately 400 RPM until failure or until 6-7 million stress cycles (revolutions) were accumulated. A magnetic counter was used to record the number of cycles. A limit switch was used to stop the machine when a polished rod fractured.

Test Schedule

Fatigue tests were conducted to determine the effects of three combinations of polished rod clamps and bolt torques as shown below:

	Clamp Designation	No. Bolts	Clamp Style	Bolt Torque	Clamp Load at Slippage
Case 1	1-1/4" Fig. 2	2	Indention	100 ft-lb	35,000 lb.
Case 2	1-1/4" Fig. 2	2	Indention	250 ft-lb	60,000 lb.
Case 3	1-1/4"	2	Friction	230 ft-lb	35,000 lb.

Case 1 represents a properly installed indention clamp. Case 2 represents an indention clamp which has been over-tightened - a field practice commonly encountered. Case 3 represents a properly installed friction clamp capable of sustaining the same 35,000 lbs. of polished rod load as the indention clamp in Case 1. The bolt torque for Case 3 was determined from clamp load tests shown in Fig. 6.

Test Results

Case 1: Fig. 2 Indention Clamp with 100 ft-lb Bolt Torque

The S-N curve for the five fatigue tests conducted for Case 1 is shown in Figure 7. Four of the polished rod specimens, H60A through H30A, fractured. Sample H25A, which endured more than 6 million cycles, did not fracture. Therefore, the endurance limit for Case 1 was estimated to be 26.5 ksi which is halfway between test H30A, the last specimen to fracture and, H25A, the first sample that did not fail.

Photographs of the four fractured samples are shown in Figures 10(a) and 10(b). Each is marked to identify crack initiation sites, crack progression and final fracture zone. In every case, crack initiation sites corresponded to clamp contact points similar to the one shown in Figure 11 for sample H60A. Samples with highest stresses, H60A and H50A, had four crack initiation sites while samples with lowest stresses, H40A and H30A, had only three crack initiation sites.

The clamp contact points were obviously regions of greatest stress concentrations. In samples H60A and H50A, the combination of this stress concentration and bending was sufficiently high that cracks originated at all four clamp contact points. But in samples H40A and H30A, the combination of stress concentration and bending were lower, causing cracks to initiate at only three of the clamp contact points.

Case 2: Fig. 2 Indention Clamp with 250 ft-lb Bolt Torque

The S-N curve resulting from polished rods tested with the Fig. 2 indention clamp tightened to 250 ft-lb is shown in Figure 8. Two samples were tested. One, H30B, fractured. The other, H25B, ran almost 7 million cycles without fracturing. Additional samples were not tested because it was possible to estimate the endurance limit from these two data points. The endurance limit was estimated to be 28.0 ksi, the stress halfway between H30B and H25B.

Figure 12 is a photograph of the fractured sample which shows four crack initiation sites. As in Case 1, crack initiation sites corresponded to clamp contact points which are the areas of greatest stress concentration.

Case 3: Friction Clamp with 230 ft-lb Bolt Torque

Figure 9 shows the S-N curve generated by testing the friction style clamp. All three test samples, C50, C30 and C25 fractured. Samples were not tested below stress levels of 25.0 ksi because rotating deflection plates for lower stresses were not anticipated. Therefore, all that is known for certain is that the endurance limit for Case 3 must be less than 25.0 ksi. However, based on the rate that the slope of the S-N curve is approaching zero, a reasonable estimate is that the endurance limit is about 22.0 ksi.

Fractured samples for Case 3 are shown in Figures 13(a) and 13(b). The number of crack initiation sites are five, three and one for samples C50, C30 and C25, respectively. Figure 14 is a photograph of sample C50 showing wear marks or fretting resulting from interference between the clamp I.D. and the O.D. of the polished rod. Ten similar marks were observed on this sample. The five crack initiation sites correspond to five of the ten wear (fretting) marks.

Figure 15 shows the friction style clamp in the open position. Corresponding wear marks on the clamp are clearly visible and are explained by the fact clamping forces were not perfectly distributed over the entire surface of the clamp.

Neither the clamp I.D. nor the polished rod O.D. is perfectly round. As a result, the clamp and polished rod have high and low contact spots. Therefore, this test suggests it may be difficult to achieve an absolutely uniform stress distribution on a friction clamp with conventional machining tolerances. The high spots became clamp contact points with the greatest stress concentrations which, in combination with bending, cause crack initiation sites.

Case Comparisons:

S-N curves for all three cases are shown in Figure 16. Based on the results of Case 1 and Case 3, the friction clamp reduced the polished rod endurance limit to a lower level than the indention clamp. This implies that a friction clamp is more detrimental to polished rods subjected to the same bending stress. A more conservative interpretation is that the indention clamp is certainly not any more detrimental to polished rods than the friction clamp.

Results in Case 2 were surprising. Logically, it was expected that overtightening the indention clamp would increase the stress concentrations and reduce the endurance limit of the polished rod. However, the opposite occurred, and the endurance limit in Case 2 increased relative to Case 1. A conservative conclusion would be that overtightening did not have any significant detrimental effect.

The degree of fretting or rubbing between the clamp and the polished rod was obviously greater in Case 3 than in either Case 1 or 2. This suggests that friction clamps may be more prone to fretting and that fretting is more detrimental to a polished rod than localized stress concentrations created by indention clamps. It's possible that the best clamp designs may generate the least amount of fretting.

Stress Concentration Factor (k)

The stress concentration factor, k, is defined as the ratio of the endurance limit of a test specimen that is free of stress concentrations to the endurance limit of the same test specimen that is subjected to stress concentrations (Ref. 3). If $k>1.0$, then stress concentrations, from whatever source, are detrimental to the fatigue life of the test specimen. The most severe stress concentrations produce the greatest stress concentration factors and the shortest fatigue life.

To determine k, it was necessary to measure the endurance limit of a polished rod without a polished rod clamp. Several attempts were made to measure this natural or "best possible" endurance limit. However, success was somewhat limited.

A "clampless holder" consisting of a hardened steel sleeve was substituted for the polished rod clamp as shown in Figure 5(b). The sleeve was designed to provide a rigid mount around the polished rod without inducing stress concentrations associated with either an indention or friction clamp.

The fit between the O.D. of the polished rod and I.D. of the sleeve was never adequate to eliminate movement between the sleeve and the polished rod. As a result, fretting action loosened the fit during the course of the longer tests. Therefore, it was impossible to maintain a constant bending stress at the junction of the sleeve and the polished rod.

In spite of this difficulty, three samples were tested as shown in Figure 17. Sample S55 fractured just before 200,000 cycles. In this case, the bending stress remained constant because the duration of the test was so short. Samples S36 and S31 endured approximately 4 million and 7 million cycles respectively. Neither fractured. However, the bending stresses for S36 and S31 decreased from S36A to S36B and from S31A to S31B over the course of the tests.

Neglecting any effects that may have been introduced as a result of the stresses declining in S36 and S31, a reasonable conclusion is that the natural endurance limit for the polished rod is somewhere between 37.0 ksi and 55.0 ksi.

The polished rod material used in this investigation, AISI 1045 carbon steel, has an ultimate tensile strength of approximately 119 ksi. This value was determined by performing a tensile test on one of the polished rod samples. Empirical data (Ref. 4) indicates that the endurance limit for this material should be about 40% to 50% of the ultimate tensile strength. Therefore, the natural or base endurance limit was assumed to be 50 ksi for purposes of calculating the stress concentration factors. Credibility of this assumption is reinforced by the fact that the theoretical endurance limit does lie between the results of S36 and S55 even though test S36 was not a total success.

Based on the assumption that the natural or best possible endurance limit, S_e, is 50.0 ksi, then stress concentration factors, k, for all three cases were calculated by using the equation:

$$k = S_e/S_e' \qquad \text{(EQ. 1)}$$

where S_e' is the endurance limit for each of the polished rods in Cases 1, 2 and 3.

Case	S_e	S_e'	k
1	50.0 ksi	26.5 ksi	1.89
2	50.0 ksi	28.0 ksi	1.79
3	50.0 ksi	22.0 ksi	2.27

Application of the Stress Concentration Factor

How to Minimize Polished Rod Breaks (Ref. 1) explains the damaging effects of bending stresses on the fatigue life of a polished rod. Example 2 in that paper illustrates the use of the Goodman Diagram to estimate the effects of bending. This Goodman

Diagram is reproduced as Figure 18. The progressively detrimental effect of bending the polished rod through 5° is clearly shown at a stress concentration factor of 1.00. (Note: In Example 2, the endurance limit was assumed to be S_e = 45 ksi as shown in Figure 18. This value should not be confused with the endurance limit S_e = 50 ksi used to calculate stress concentration factors for Cases 1, 2 and 3.)

In Example 2, deflection of about 4° is enough to exceed the allowable stress and cause a fatigue failure. However, the estimate in this calculation is optimistic because the stress concentrations caused by the polished rod clamp are neglected.

When stress concentrations introduced by polished rod clamps are considered, a more realistic picture is presented as shown in Figure 19. Here the usual convention of multiplying S_a by k is followed (Ref. 3).

Figure 19 illustrates the bending limit that can be tolerated for an indention clamp in Case 1 with k = 1.89 is only slightly greater than 2°. The bending limit for the friction clamp with k = 2.27 is even less.

Comparison of Laboratory and Field Fractures

Obviously, the laboratory method used to generate stress in polished rods is different than actual field conditions. As a result, some differences exist between the fracture patterns in the laboratory and those that occur in the field.

By deflecting the free end of the polished rod in a circular pattern on the bench test, ***each point*** on the perimeter of the polished rod at the face of the clamp was subjected to the same fully reversed stress cycle. Under field conditions the stress cycles are created by a combination of axial and bending stress on a polished rod that is usually not rotated so that only ***one point*** on the perimeter is subjected to the maximum stress cycle.

Most of the laboratory fractures have ***multiple*** crack initiation sites spaced around the perimeter of the polished rod. Sample H60A in Figure 10(a) is a good example. Multiple crack initiation sites grew radially inward and finally resulted in a fracture near the ***center*** of the polished rod.

Polished rod breaks that occur under field conditions nearly always have only ***one*** crack initiation site. The fractured polished rod shown in Figure 20 is typical. Rub marks on the top segment in this picture indicate the clamp was installed with this segment lower than the other. The uneven bottom face resulted in bending in the polished rod in addition to the normal axial load. The combination of bending and tension caused a critical fluctuating stress at a ***single*** point on the polished rod perimeter adjacent to the rub mark on the clamp. This became the initiation site for the crack which then propagated across the polished rod until fracture occurred on the side ***opposite*** the crack initiation site.

The effects of stress concentration and bending are the same for the laboratory and the field even though loading conditions are different. Fatigue cracks initiate at points where the localized stresses are the greatest. Any number of crack initiation sites should be anticipated in the laboratory because the applied stress range is ***uniform*** around the perimeter of the polished rod. Stress concentrations created by the clamp contact points determine the number and location of the crack initiation sites. On the other hand, single crack initiation sites should be expected in the field because the maximum stress range occurs at a ***single*** point on the polished rod perimeter.

It is not clear if the laboratory or the field represents a worst case scenario. Based on observations made in this study, it cannot be determined if stress concentration factors in absolute terms are the same for the laboratory and field conditions. However, it is reasonable to expect that stress concentrations determined in the lab will occur in the same sequence in the field.

Spray Metal Polished Rods

Laboratory testing was performed on short lengths of AISI 1045 "piston steel" polished rods. Testing was not performed on polished rods with flame-sprayed Nickel-Chromium hard surface coatings. Serious problems are always encountered if polished rod clamps are installed on these "spray-metal" finishes.

A spray metal surface is a thin, very hard coating applied over softer metal for the purpose of resisting abrasion and corrosion. Radial loads imposed by the clamp crack the hard coating as shown in Figure 21. These cracks are stress risers and greatly increase the probability of a fatigue failure. In addition, any clamp will have to be excessively tightened on the hard surface in order to achieve rated load capacity. These excessive compressive loads can damage the clamp as well as the polished rod.

Conclusions

1. ***Bending at the carrier bar and clamping on spray metal surfaces are the leading causes of polished rod failures.*** The use of leveling plates between the carrier bar and the polished rod clamp and checking that the segments on the bottom of the polished rod clamp are even are simple, yet effective methods of managing polished rod bending stresses. ***Clamping on the spray metal surface of a polished rod can result in fatigue failures, even if bending stresses are not present.*** Polished rod clamps should never be installed on the spray metal surface.

2. *Indention clamps have lower stress concentration factors than friction clamps.* Therefore, indention clamps are the best choice. However, even with an indention clamp, the polished rod cannot tolerate much more than 2° of bending at the carrier bar.

3. *Over tightening an indention clamp does not increase the stress concentration*

factor. However, a good policy is to always follow the manufacturer's recommended procedure and apply no more bolt torque than necessary to achieve the clamp's rated load capacity.

NOMENCLATURE

k	Stress concentration factor for fatigue
S_a	Amplitude of fluctuating stresses (ksi)
S_e	Endurance limit without stress concentration effects (ksi)
S_e'	Endurance limit with stress concentration effects (ksi)
S_m	Mean or average value of fluctuating stresses (ksi)
S_u	Ultimate tensile strength (ksi)

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L. A.

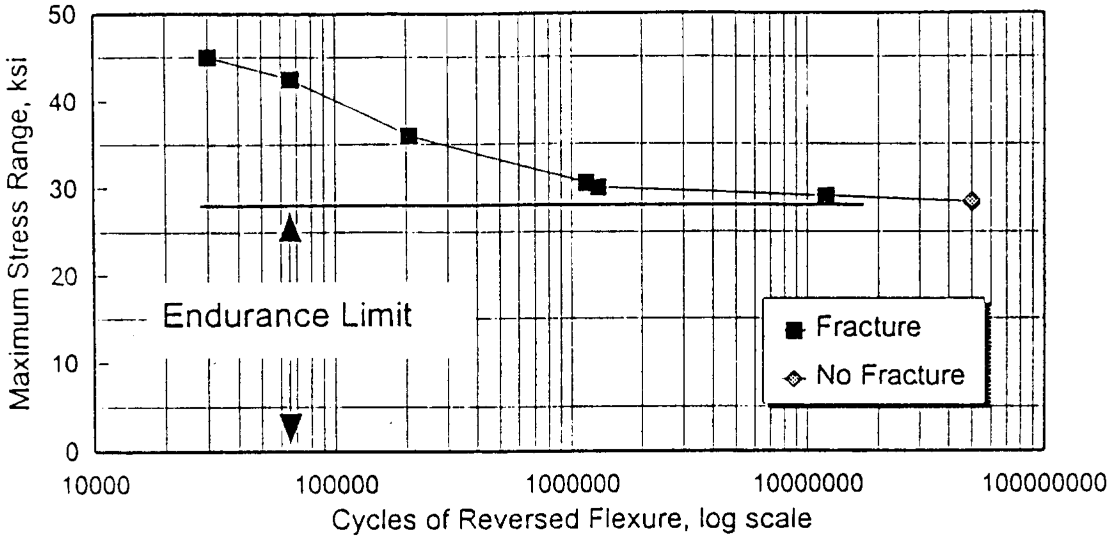

Figure 1 - Typical S-N Curve
Structural Steel Rod, As Rolled

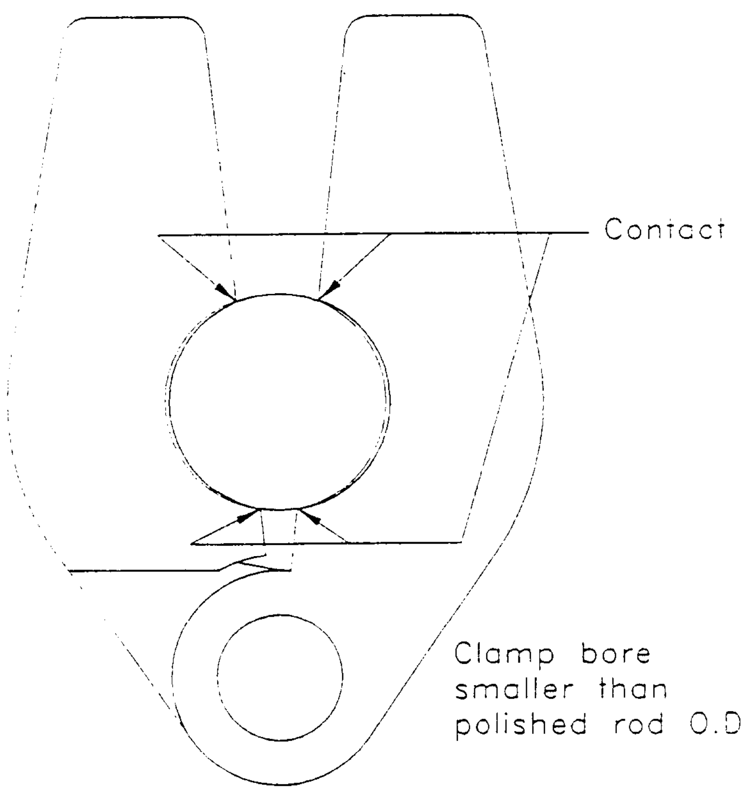

Figure 2a - Huber Fig. 2 Indention Style Clamp
Four Contact Points Per Land

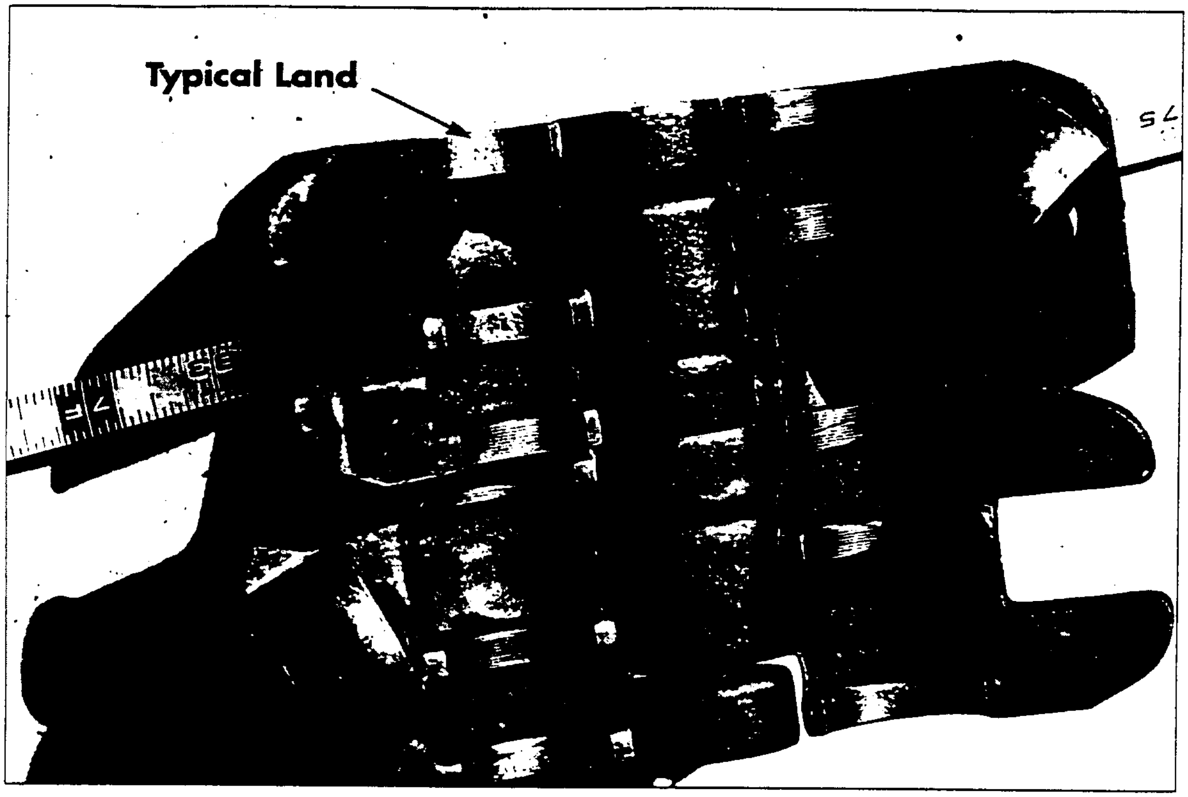

Figure 2b - Huber Fig. 2 Indention Style Clamp

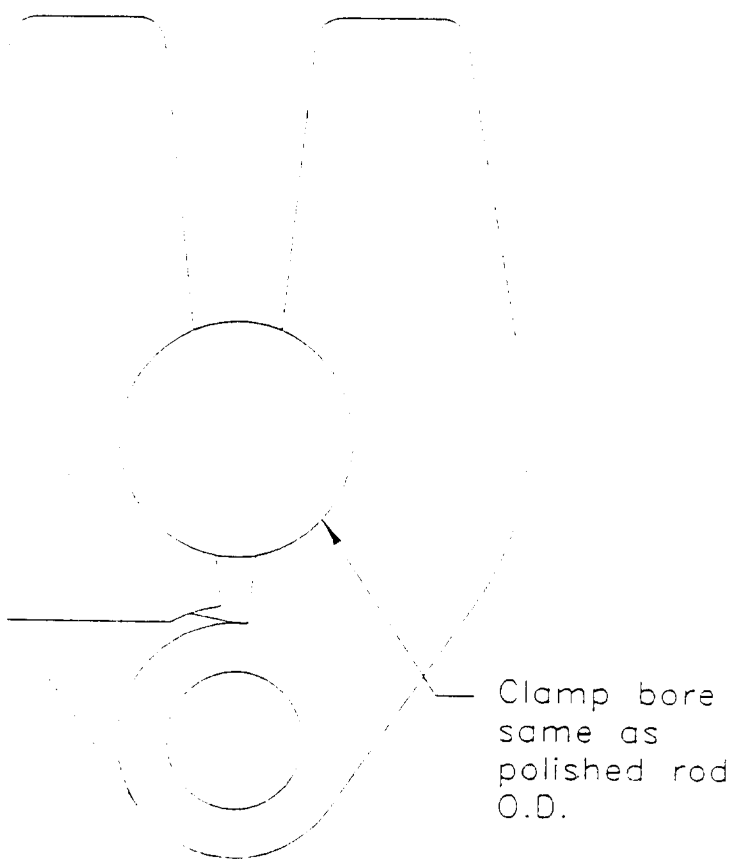

Figure 3 - Friction Style Clamp

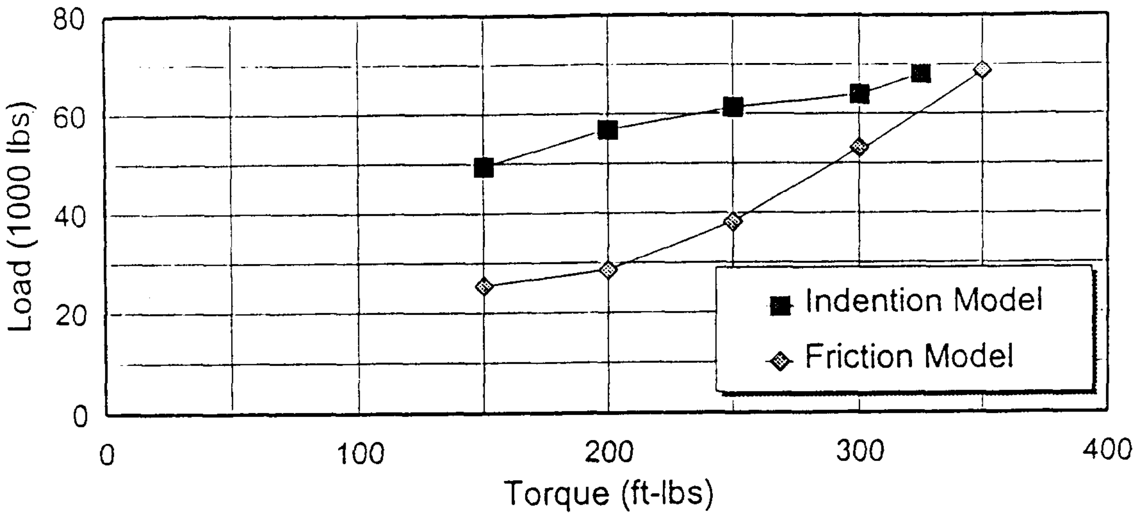

Figure 4 - Load to Slippage vs. Bolt Torque
1-1/4" Indention (Huber Fig. 2) & Friction Models

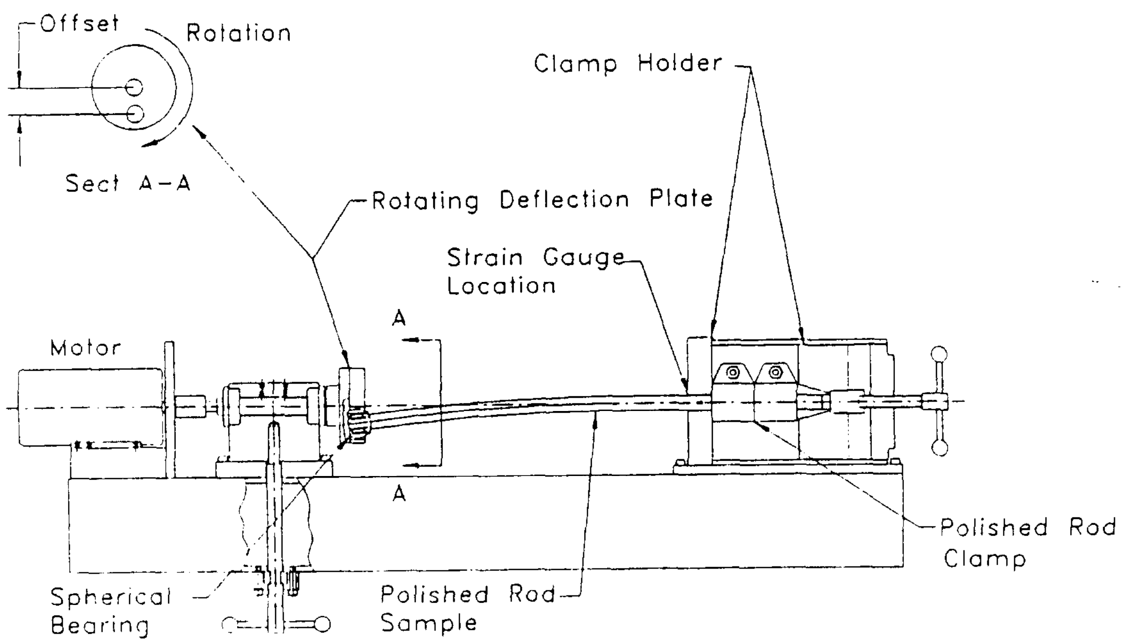

Figure 5a

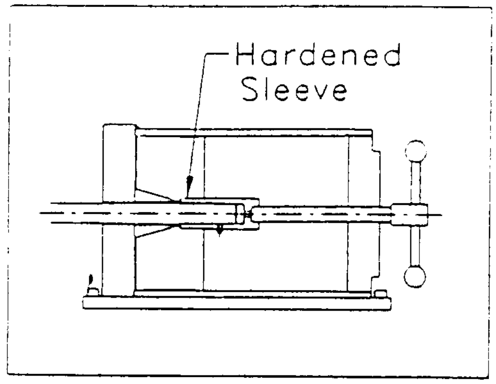

Figure 5b

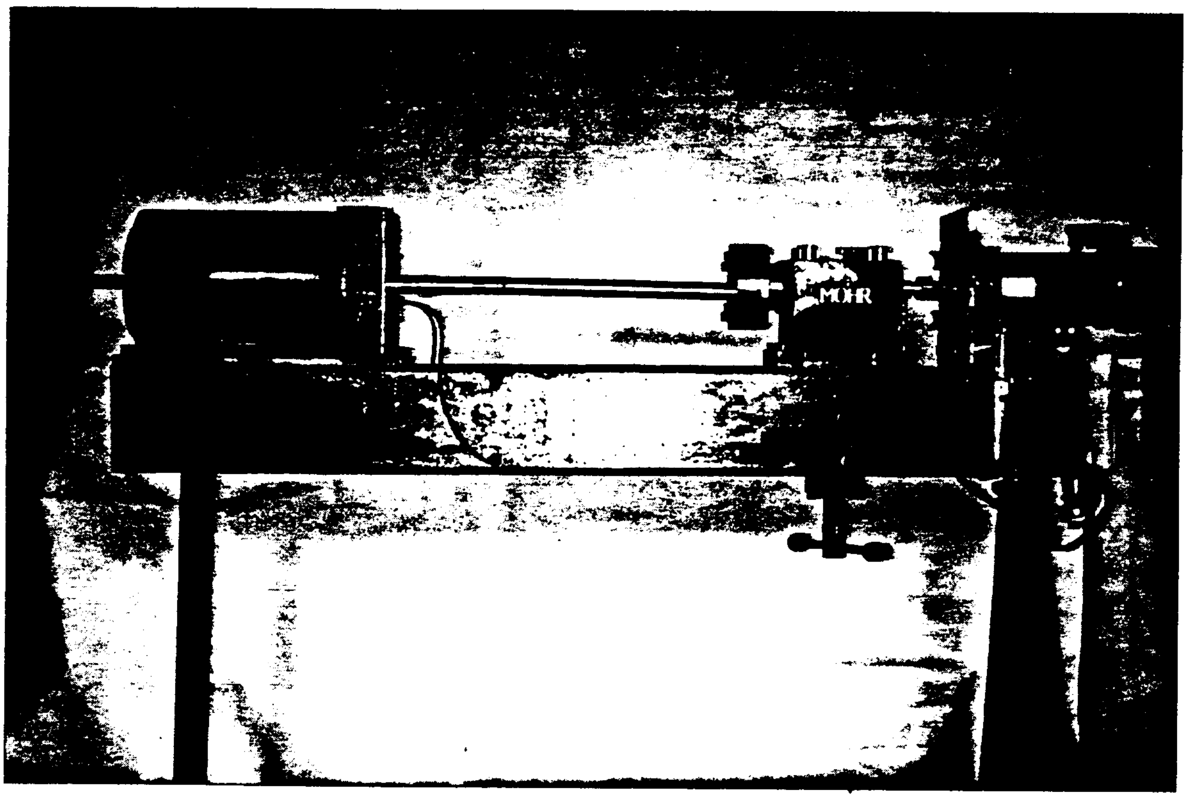

Figure 5c - Experimental Apparatus
Polished Rod Fatigue Testing

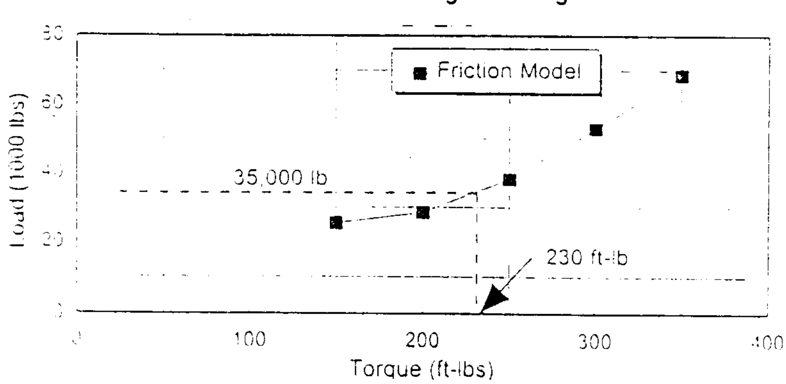

Figure 6 - Load to Slippage vs. Bolt Torque
1-1/4" Friction Model

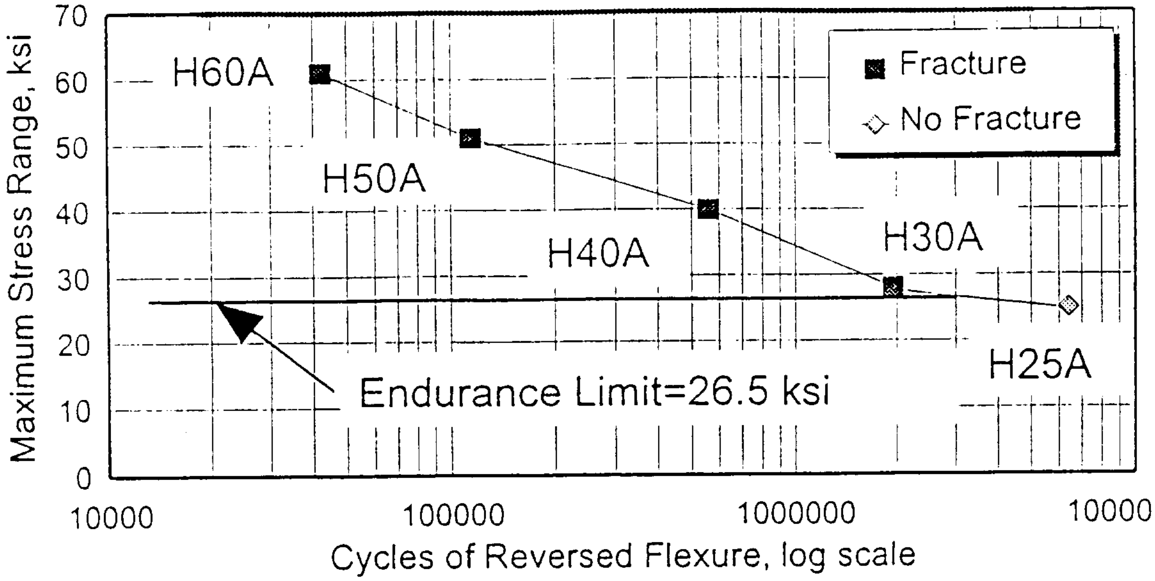

Figure 7 - Stress-Cycle Curve
Huber Fig. 2 Clamp, 100 ft-lb

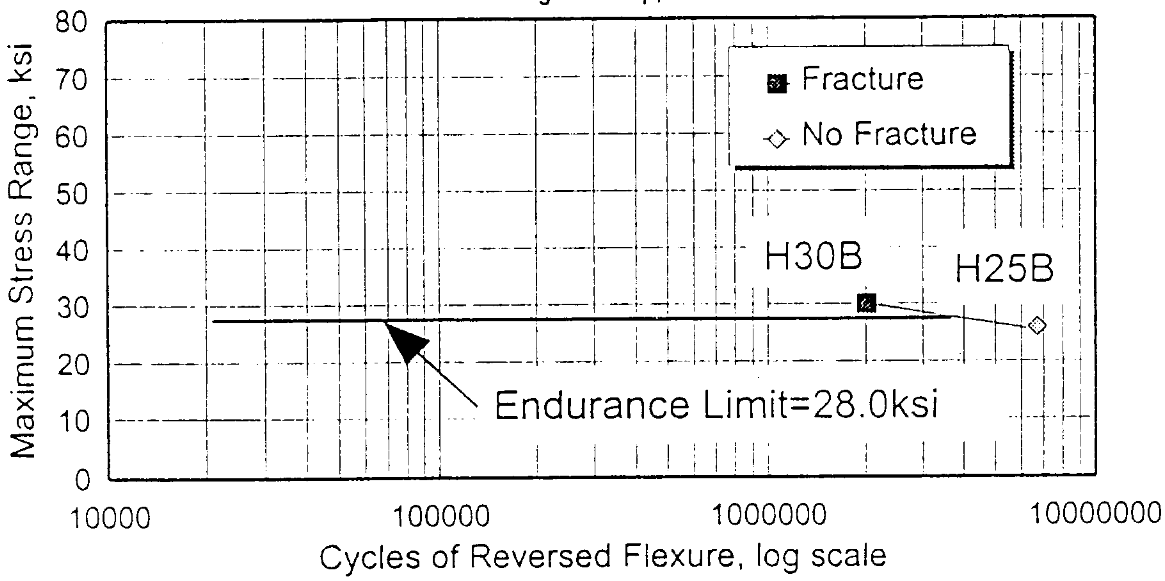

Figure 8 - Stress-Cycle Curve
Huber Fig. 2 Clamp, 250 ft-lb

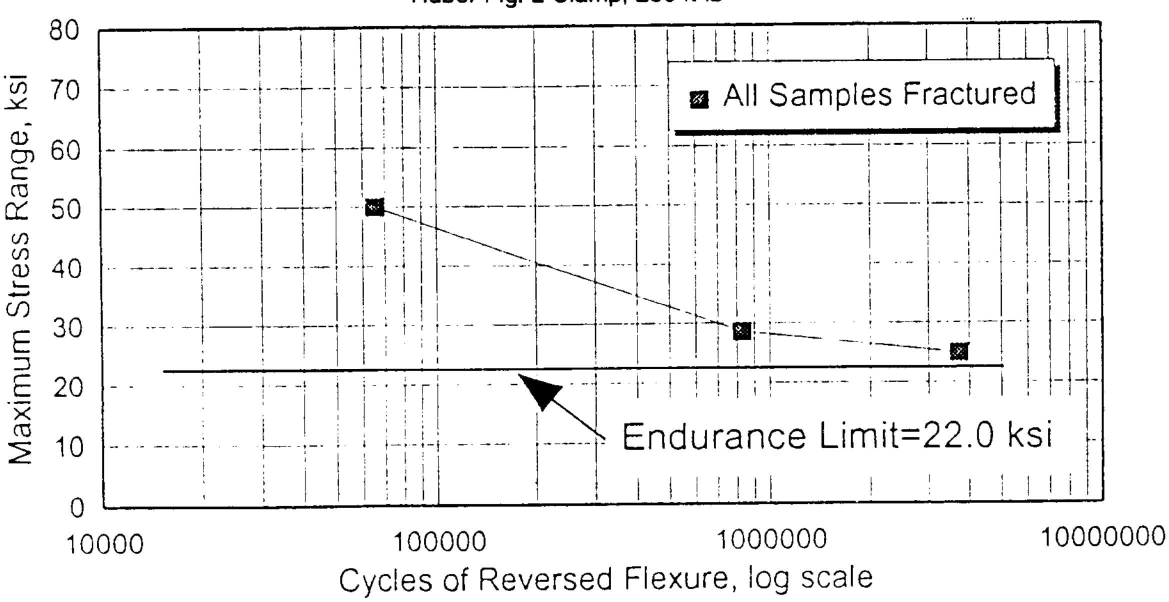

Figure 9 - Stress-Cycle Curve
Friction Style Clamp, 230 ft-lb

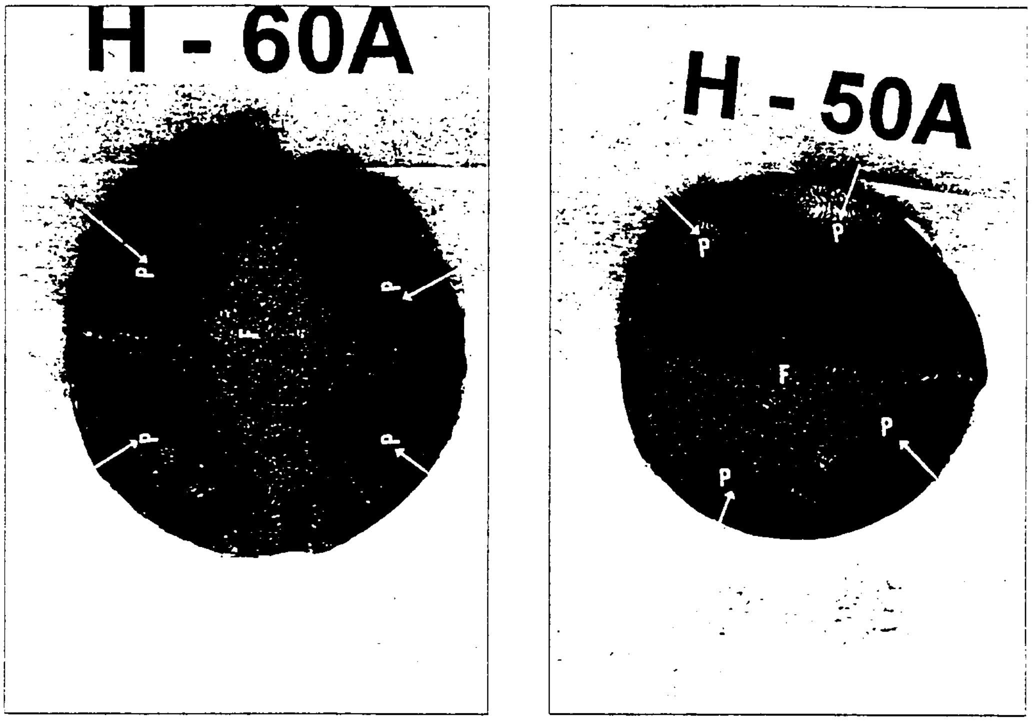

Figure 10a - Fractured Samples H60A and H50A
Four Initiation Sites

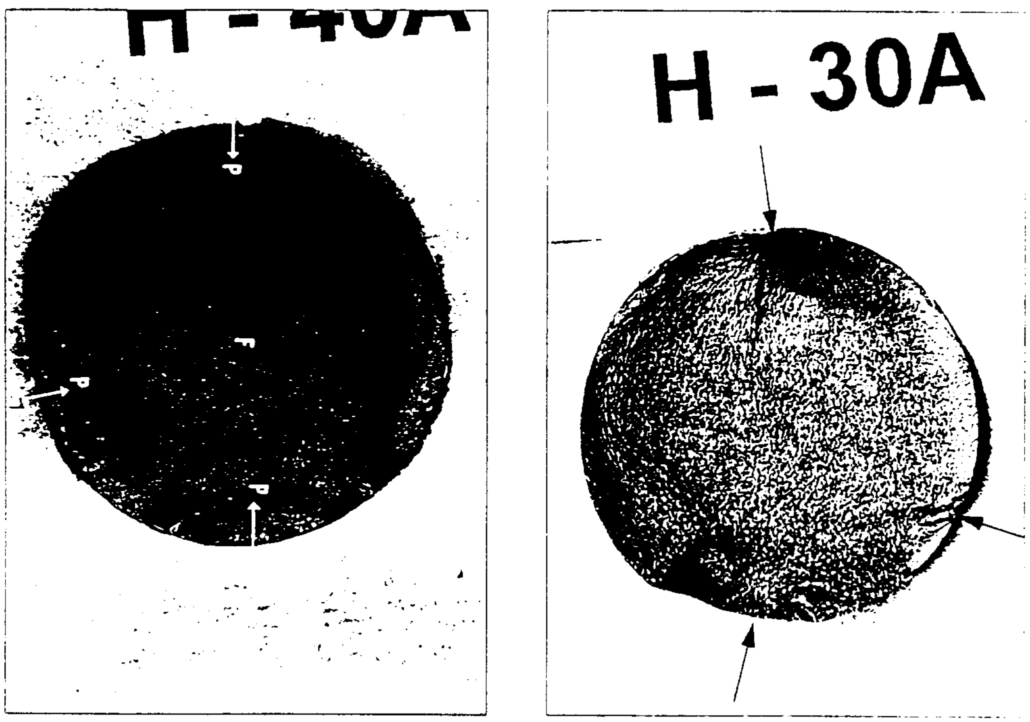

Figure 10b - Fractured Samples H40A and H30A

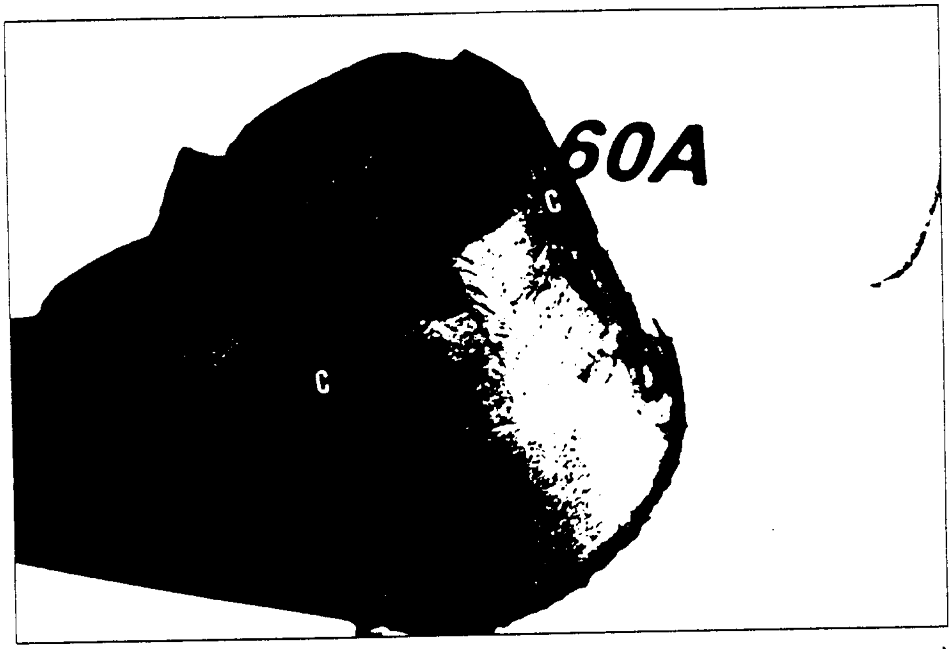

Figure 11 - Fractured Sample H60A
Showing Wear Marks (Denoted by "C")

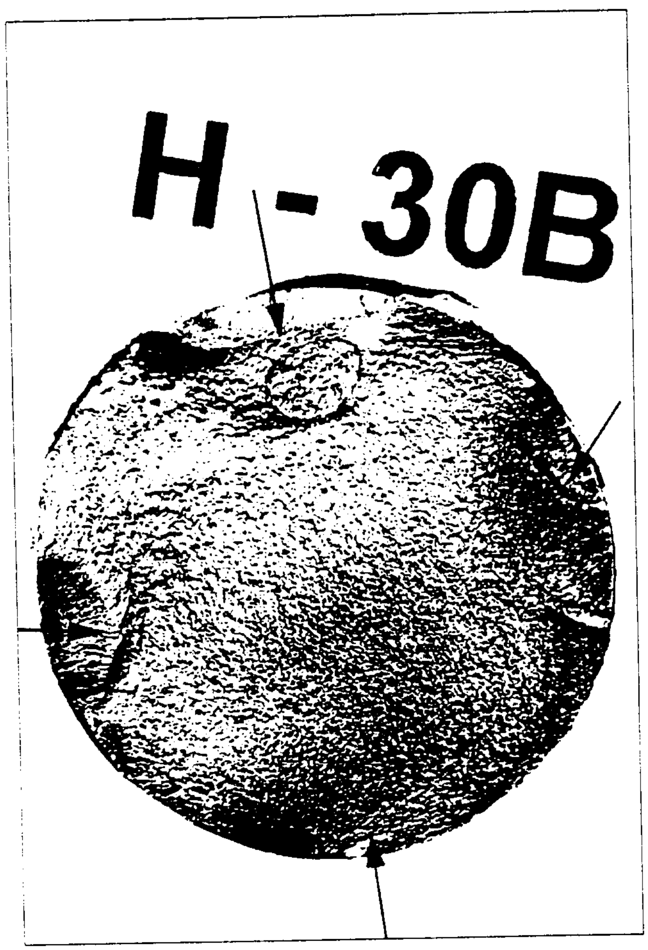

Figure 12 - Fractures Sample H30B
Four Initiation Sites

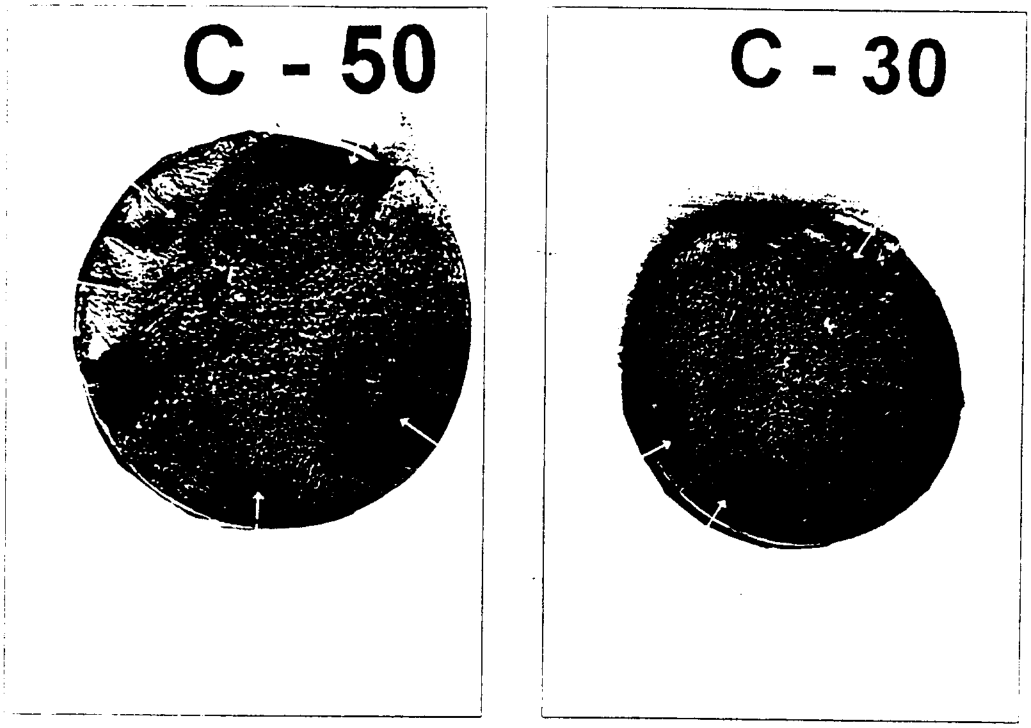

Figure 13a - Fractured Samples C50 and C30
Five Initiation Sites

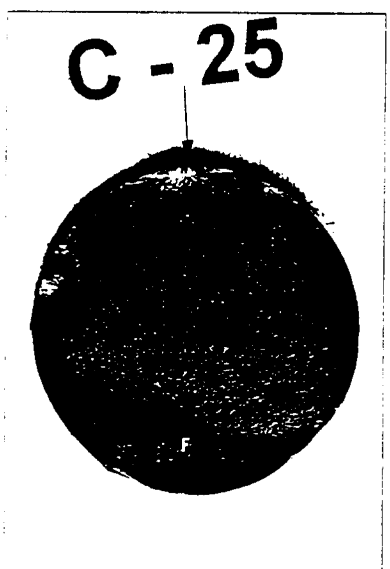

Figure 13b - Fractured Sample C25
One Initiation Site

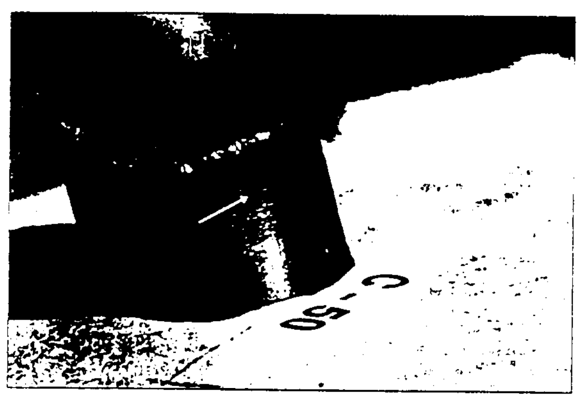

Figure 14 - Fractured Sample C50
Showing Wear Mark (At Arrow)

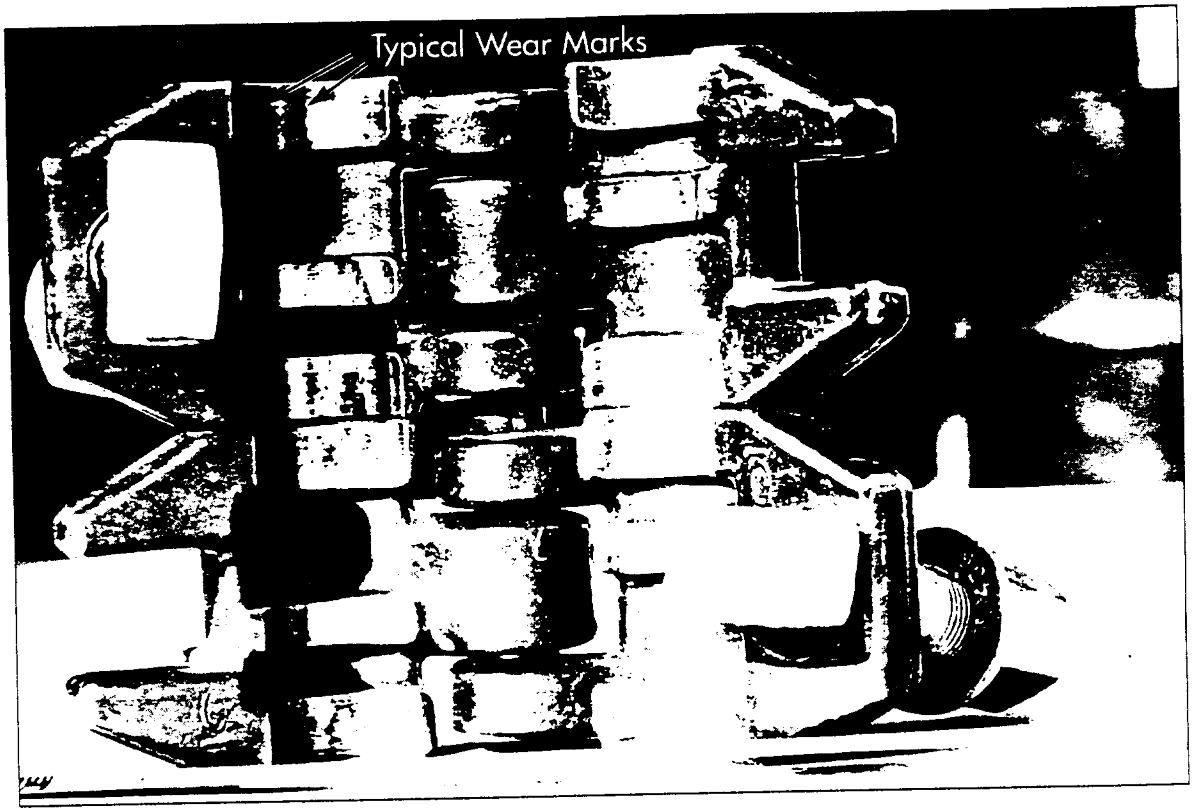

Figure 15 - Friction Style Clamp
Showing Wear Marks

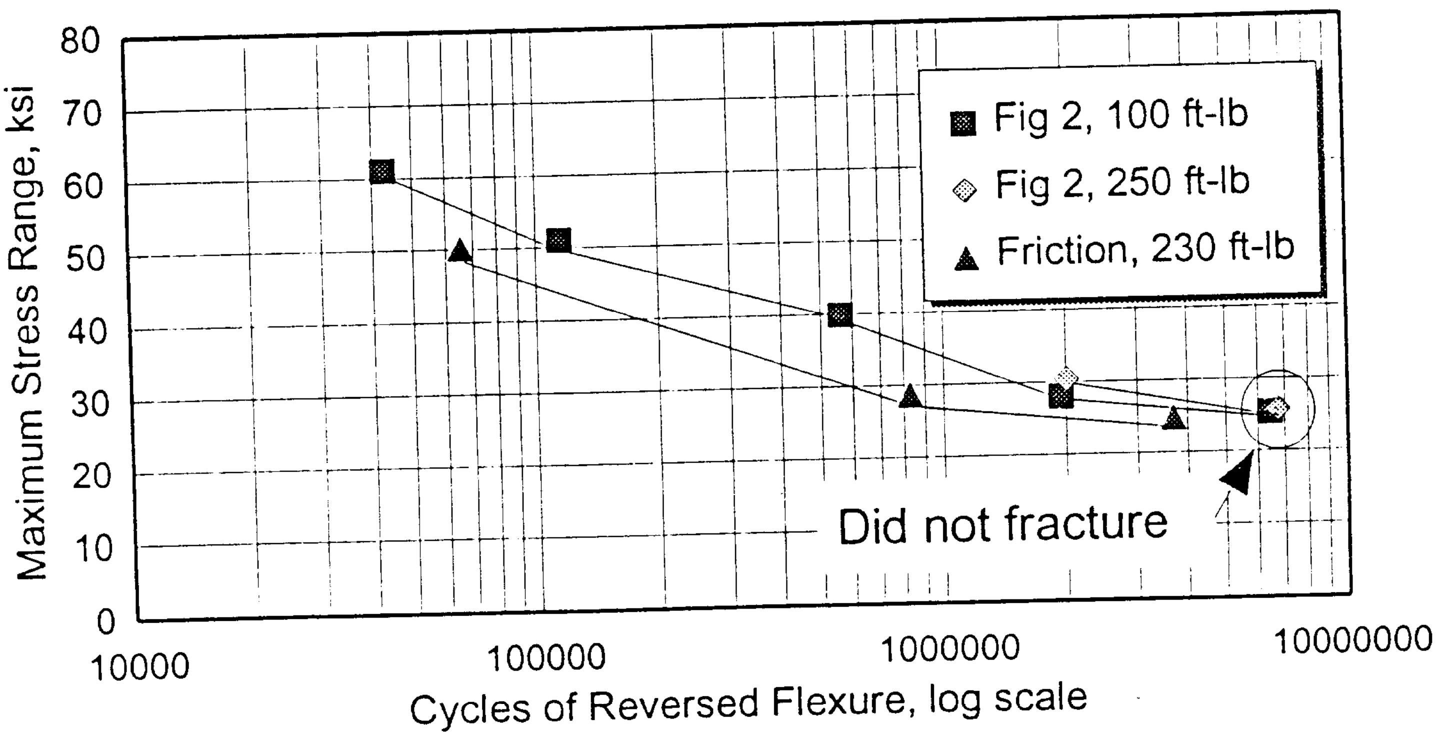

Figure 16 - Stress-Cycle Curves
Indention and Friction Models

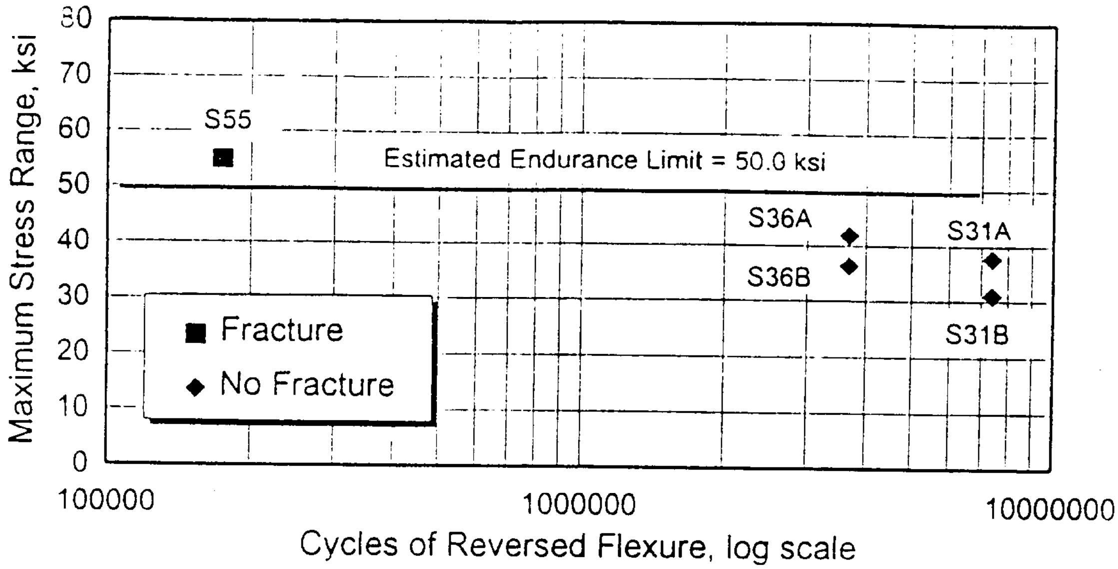

Figure 17 - Stress-Cycle Curve
Polished Rod with "Clampless Holder"

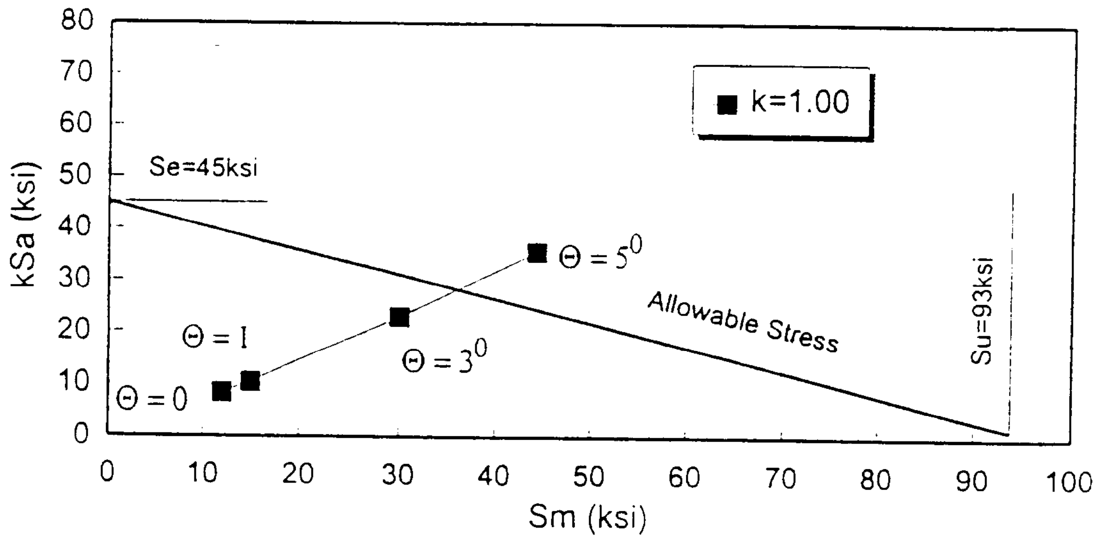

Figure 18 - Goodman Diagram
Example 2 in Reference 1

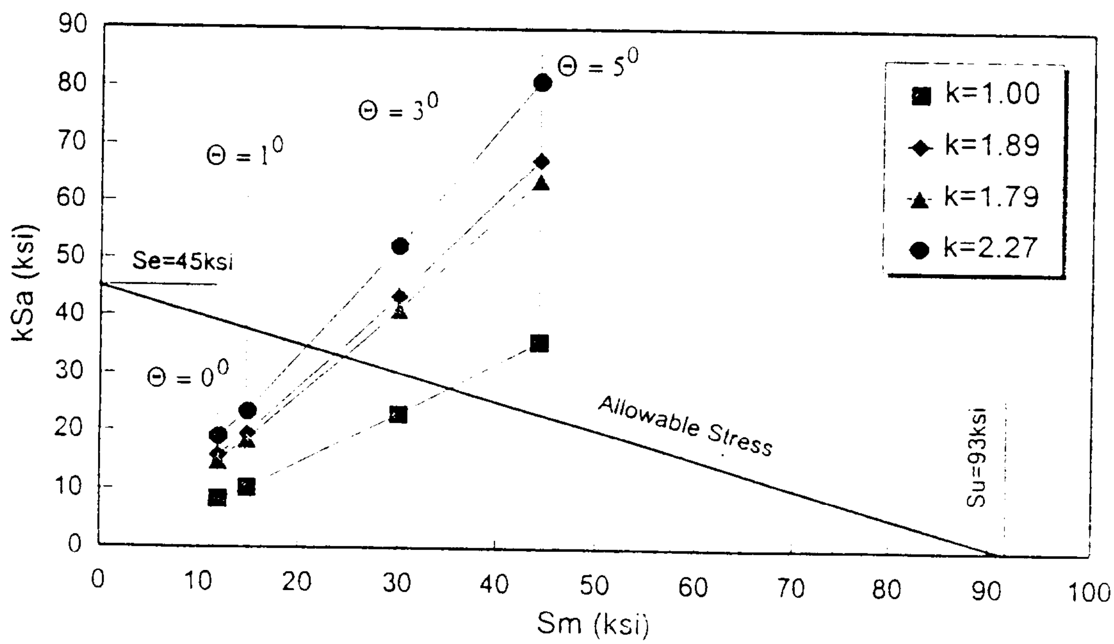

Figure 19 - Goodman Diagram for Example 2, Effects of Stress Concentration

Figure 20 - Polished Rod Fatigue Fracture
Induced Under Actual Field Conditions

Figure 21 - Clamp Induced Cracks in Surface Overlay
of a "Spray Metal" Polished Rod