

THE UNIVERSITY OF MANITOBA

THE EFFECT OF INTERFERENCE FIT ON THE DIMPLED LOADED-HOLE

FATIGUE STRENGTH OF 2024-T3 ALUMINUM ALLOY

By

Andrew P. Kuc

A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements for the Degree of
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ABSTRACT

The effect of interference fit on the fatigue strength of loaded holes is well known. Recently, a new technique has been developed for increasing this strength in thin sheet material. Briefly, the technique consists of dimpling the material centering about the region where the hole is to be made thus introducing tensile plastic strain. The dimple is then flattened and the hole drilled leaving the region around the hole under residual compressive stress.

Experiments were carried out to obtain the combined effect of interference and dimpling in loaded-hole fatigue applications.

In zero-to-tension fatigue tests on nominally 0.063 in. thick 2024-T3 aluminum alloy specimens, optimum tapered-pin interference and dimpling combined gave a fatigue strength improvement factor of 4.0 while the dimpling technique increased the fatigue strength by a factor of 2.85 all at 10^6 cycles to failure.

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NOMENCLATURE

- P - applied pin load
 d - nominal pin and hole diameter
 D - width of lug
 H - head height of lug on loaded side of hole
 t - thickness of lug
 δ - initial difference between mating pin and hole diameters
 S_m - mean stress
 S_a - alternating stress
 S_{NET} - net stress
 S_{MIN} - minimum stress
 S_{MAX} - maximum stress
 S_{NOM} - nominal applied stress over the minimum net section
 N - cycles to failure
 K_f - fatigue strength reduction factor
 K_t - theoretical stress concentration factor
 a - a material constant representing the half length of a fictitious "building block" or "equivalent grain" of the material
 r - hole radius
 S_{INT} - initial interference hole boundary hoop stress
 P_a - alternating pin load
 P_m - mean pin load
 $S_{a,NOM}$ - nominal alternating stress over the minimum net section

CHAPTER 1

INTRODUCTION

1.1 Introduction

Since the introduction of machinery, mechanical elements, subjected to fluctuating loads, have been a victim of a mode of failure characterized as fatigue. Failure is abrupt and may occur in both a ductile and a brittle metal and at stresses substantially below the yield point of the material. Small wonder that investigators have spent over a century in attempting to understand the nature of and find the remedy to fatigue.

Metallurgical research conducted on the microscopic level has led to the acceptance of two failure mechanisms based on the popular Dislocation Theory. They are the nucleation of microcracks through the process of slip and the propagation of microcracks by the rupturing of atomic bonds at the crack tips through the action of applied tensile stresses normal to the crack plane. Numerous fatigue tests, on the other hand, have provided a storehouse of data on the macroscopic fatigue properties of particular materials. Surface finish, type of loading, nature of load fluctuation, grain size and orientation, size of part, and atmospheric environment are but a few of the many variables found to affect these properties. Yet, despite the vast amount of knowledge and empirical data available, the complexity of fatigue has permitted mechanical designers to only crudely approximate the fatigue strengths or service lives of even simple components.

In fatigue, damage begins in the portions of the material which cannot support the applied stresses experienced therein. Fatigue is therefore a localized phenomenon. Consequently, microcracks tend to form at points of stress concentration. On the microscopic level, these may be represented by grain boundaries, voids, or other discords in atomic matrix. On the macroscopic level, holes, fillets, grooves, threads, seams, keyways or any one of a number of discontinuities required by design in the shape of a part are almost invariably the origins. Once microcracks have reduced a loaded cross section sufficiently, the remaining undamaged material in the section may suffer a brittle fracture.

At one time, if a part failed in fatigue it was simply replaced by a larger, stronger one. If this proved inconvenient, the design was altered. In engineering, and particularly where size and weight are crucial factors, it is desirable for a machine element to display a high fatigue and/or static strength to weight ratio. To accomplish the former in the presence of stress concentrations, beneficial residual compressive stresses are generally induced in the critically stressed material about the concentrations. Applied loads are then more evenly distributed over the cross sections in question, leading to higher joint efficiencies.

The improvement of fatigue strengths or the extension of service lives is still the continuing concern of much research. One is constantly striving to provide sounder guarantees on the performance of components especially when human lives may be involved. This thesis highlights a particular sample of such research.

1.2 Scope of the Present Research

The present experimental investigation proposes and examines the effectiveness of a new method for increasing the fatigue strength of loaded-hole connections in sheet material. The method entails combining two previously established techniques, dimpling and interference. Dimpling induces beneficial residual compressive stresses around concentrations and interference operates to reduce harmful stress fluctuations over the critical cross section of the loaded sheet material.

CHAPTER 2

REVIEW OF LITERATURE ON FATIGUE STRENGTHENING OF LOADED HOLES

2.1 Introduction

A major concern of mechanical designers is the harmful effect of stress concentrators on the fatigue life of components. Both an interference fit and the new technique termed dimpling have individually been proven successful in improving the fatigue strength of loaded holes by reducing the effect of the stress concentrator. A representative survey of published research involving the use of interference fits and dimpling follows.

2.2 The Interference-Fit Method

Interference will be defined throughout the entire thesis as:
 $\{d(\text{pin}) - d(\text{hole})\}/d(\text{hole})$.

An interference fit, created by the insertion of an oversized pin into a given size hole, has been studied by stress analysts and fatigue researchers alike.

Jessop, Snell and Holister (1) performed a photoelastic investigation on the variation of the hoop tensile stresses and the shear stresses in a plate around a hole boundary with pin load for the cases of a push fit and interference fits between the pin and the plate. With interference, all the mean stresses were enhanced, but the majority of the alternating

stresses were considerably reduced. Figure 2.1 illustrates the approximate distribution of hoop stress around the hole boundary as found by the above investigators for the case of a steel pin in an aluminum alloy lug. The maximum hoop tensile stress occurred on the minimum transverse section for both a push-fit pin and for the two degrees of interference. In addition, at a maximum pin load of 32×10^3 LB./IN.², the resultant maximum hoop tensile stress was reduced by approximately 20 and 34 percent with interferences of 0.003 and 0.006 inch per inch hole diameter respectively. The maximum shear stress on the horizontal diameter versus pin load is shown in Figure 2.2. The interference reduced the rate of increase of stress at low loads, but gave the normal rate for higher loads, as would be obtained for the push-fit case. Figure 2.3 presents the distribution of shear stress found around the hole boundary. The maximum shear stress for the push-fit case occurred about 30° from the horizontal diameter on the loaded side of the hole but this maximum was displaced towards the horizontal diameter as the interference was increased.

Ligenza (2) also employed photoelasticity to study the variation, with load, of the maximum hoop tensile stress on the hole boundary of the horizontal diameter in a pin-loaded, semicircular-ended lug for various amounts of interference furnished by interference-fit liners. The variation found for an interference fit bore a resemblance to the one found by Jessop, Snell and Holister. That is, the applied load changed the maximum hoop tensile stress only slightly at lower load levels and at a slight rate of increase at intermediate loads, until, at a critical level,

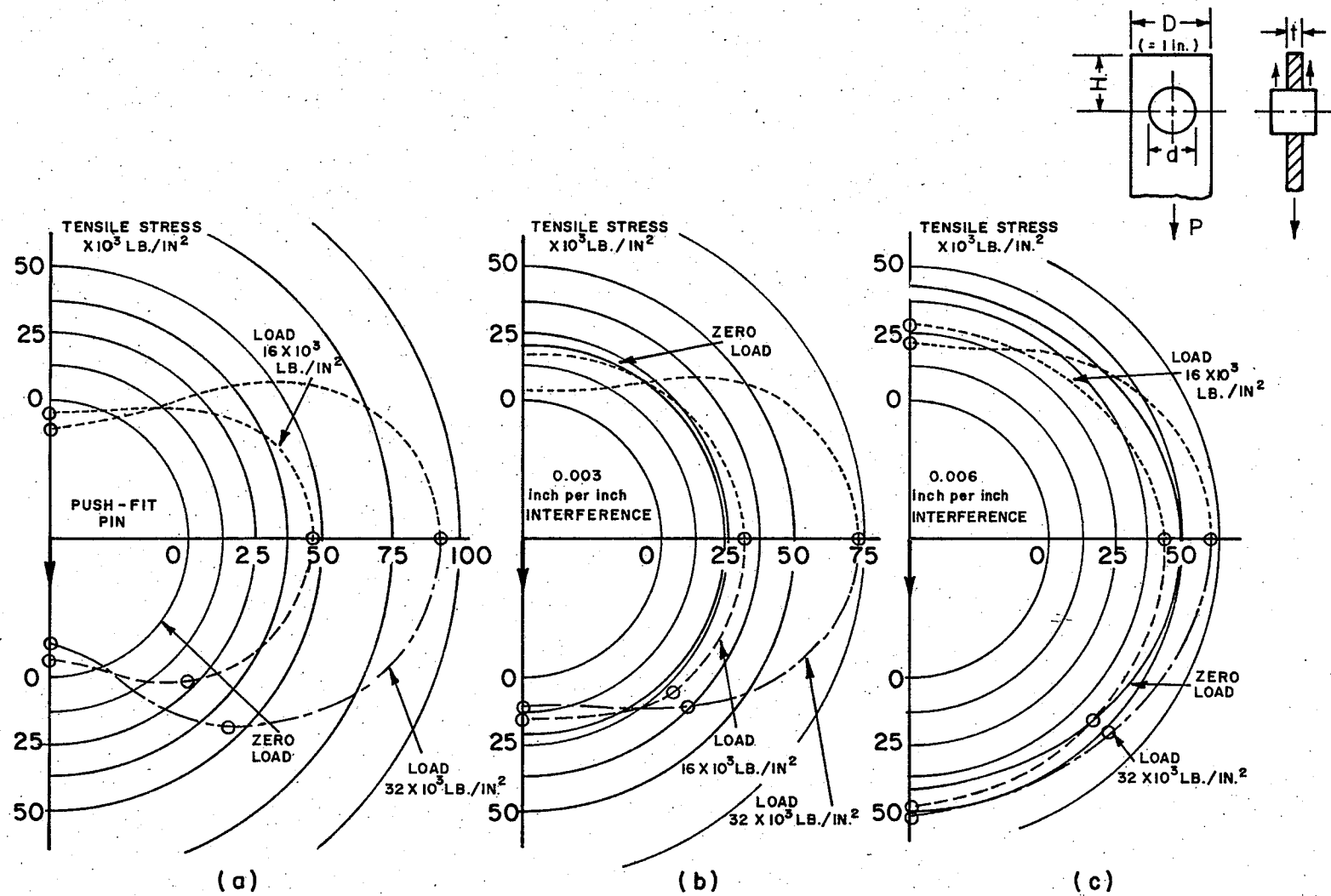


Figure 2.1 Approximate Distribution of Hoop Tensile Stress Around the Hole Boundary ($d/D = 0.375$). Stress Conditions Apply to Aluminum Alloy Lugs and Steel Pins. Photoelastic Analysis (1).

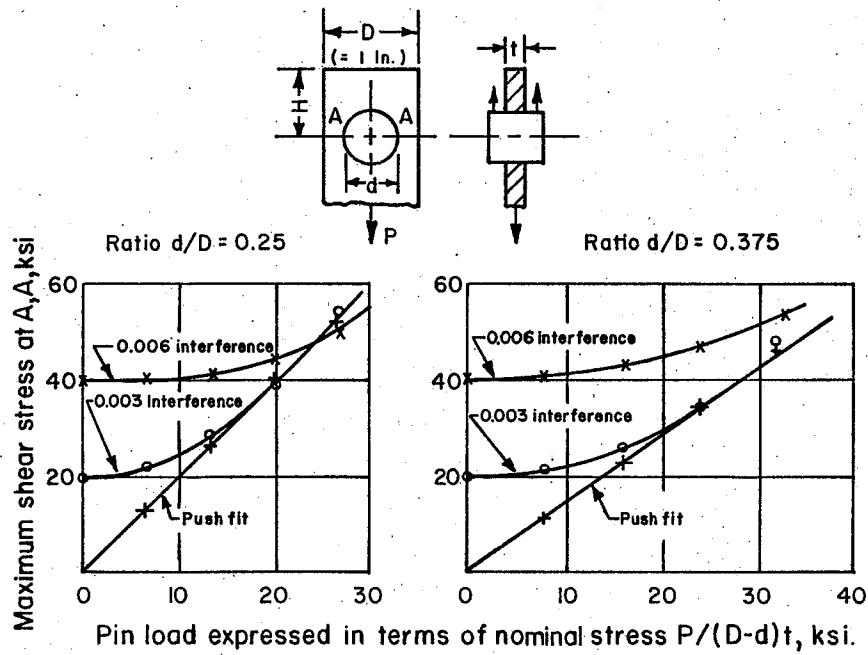


Figure 2.2 Effect of Interference on Maximum Shear Stress on Horizontal Section of Lug (1)

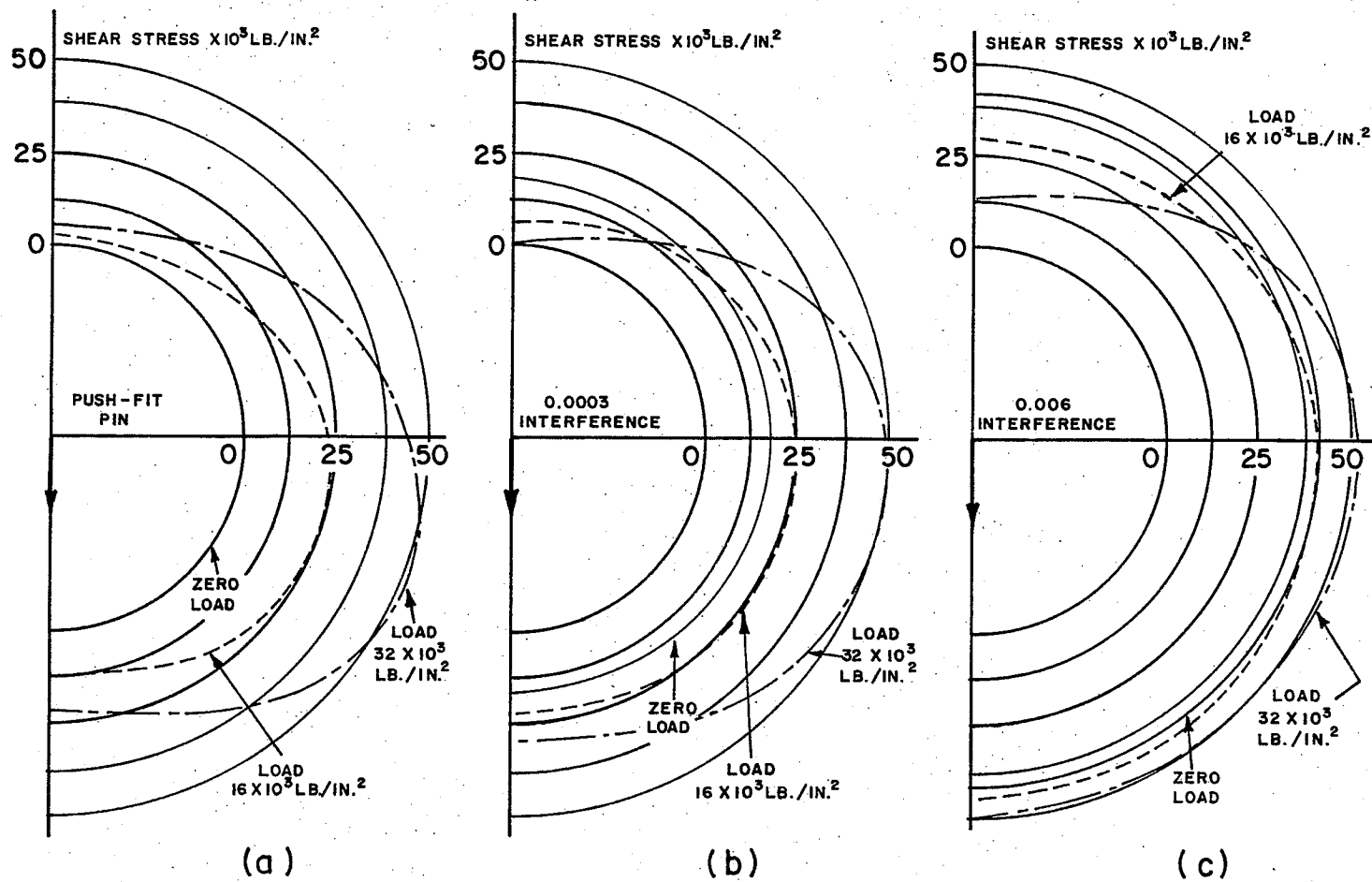


Figure 2.3 Distribution of Shear Stress Around the Hole Boundary ($d/D = 0.375$), (1)

the stress became proportional to load, as shown in Figure 2.4. Based upon the measurements of the variation of maximum hoop tensile stress with load at various levels of interference and for several lug configurations, Ligenza showed that interference fits could be used to combat fatigue within pin-loaded lugs by reducing cyclic-stress levels at the critical regions and that an optimum level of interference exists with each applied load for each lug-liner configuration.

Lambert and Brailey (3), with the use of photoelasticity, discovered that with an initial interference fit between pin and plate, the increase in maximum shear stress for a given increase in load increased with increasing load but that the stress-load relationship showed a distinct discontinuity. The load at which this discontinuity occurred was dependent upon both the initial interference and the coefficient of friction between the pin and the plate. A high coefficient of friction coupled with an initial interference fit effectually reduced the shear stress concentration factor.

In an early work on the effect of an interference fit on fatigue life, Fisher and Winkworth (4) showed that little improvement in fatigue life was obtained with straight-shank fasteners for interferences within shop tolerances. Later, (5), they discovered that for interferences exceeding 0.0043 inch per inch of diameter, an increase from about 300,000 cycles for a small clearance to non-failure in 10,000,000 cycles was usually obtained in B.S. L65 Al-Cu alloy lugs of the square-ended type subjected to fluctuating nominal tensile stresses on the minimum section

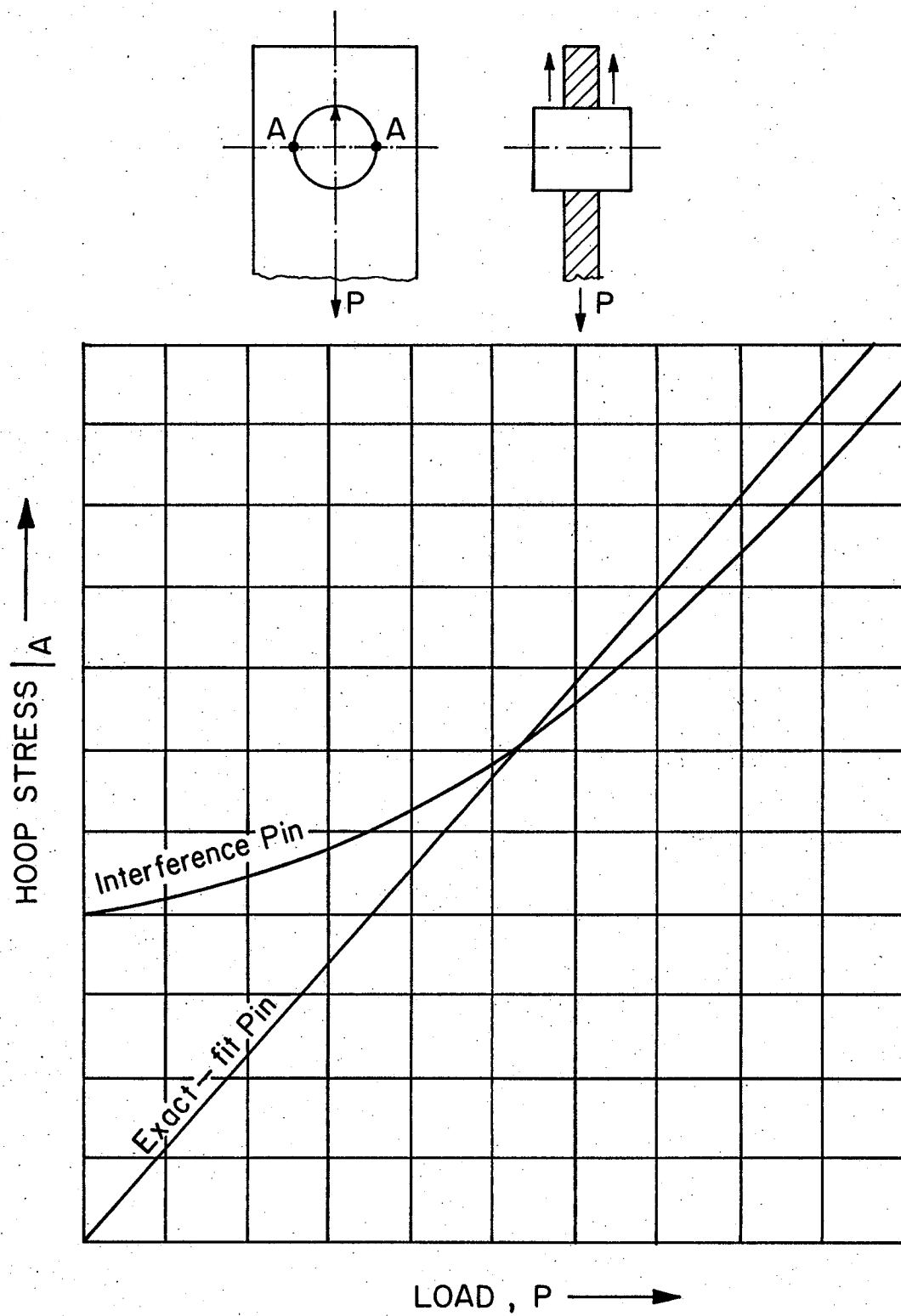


Figure 2.4 Schematic Diagram of Minimum Section, Hole Boundary Hoop Stress Versus Applied Pin Load. Photoelastic Analysis (2)

of 13.4 ± 4 ksi. This improvement was also obtained for a mild steel bush-pin combination when the interference exceeded 0.0032 inch per inch.

Schijve, Broek and Jacobs (6) also found that an interference of 0.4 percent of hole diameter was required to show a definite fatigue-life improvement in aluminum alloy lugs.

Fisher and Yoemans (7) studied the effect of interference at three mean stress levels for lugs in the Al-Cu alloy B.S. L65 and the Al-Zn-Mg alloy DTD 363. The results, entered in Table 2.1, show that a considerable improvement in fatigue strength was achieved by increasing the interference from 0.001 to 0.0043 inch per inch, the greatest increases being obtained when the mean stress was 11.2 ksi.

Conducting zero-to-tension fatigue tests, Hartman and Jacobs (8) examined the effect of interference and clearance, with life, on the fatigue strength of 24S-T Al-Cu alloy lugs. The S-N curves found are displayed in Figures 2.5 and 2.6. The maximum interference values of 0.004 and 0.0067 inch per inch tested provided fatigue strength improvement factors of 2.2 and 2.0 in comparison to clearance at 10^6 cycles to failure for the larger and smaller hole diameter-to-width of lug ratios respectively. Further, in each case, the beneficial effect of interference continually decreased as the life decreased.

From performing direct stress, tension-tension fatigue tests on square-ended lugs made from the aluminum-copper alloy B.S. L65, Low (9) observed that the fatigue strength progressively increased with increase in interference, up to an upper limit represented approximately by the

TABLE 2.1

Alternating Stresses (\pm ksi) in Aluminum Alloy Lugs
 Failing in 10^6 Cycles, Showing the Effect of Interference
 at Various Mean Stresses (7)

Row	Interference (inch/inch)	Al-Cu alloy B.S. L65 with mean stress (ksi) of			Al-Zn-Mg alloy DTD 363 with mean stress (ksi) of	
		0	11.2	16.8	11.2	16.8
A	0.001	<u>+9.4</u>	3.15	2.5	3.5	2.9
B	0.0043	<u>+13.3</u>	7.6	3.4	7.2	4.8
Ratio B/A		1.4	2.4	1.35	2.1	1.65

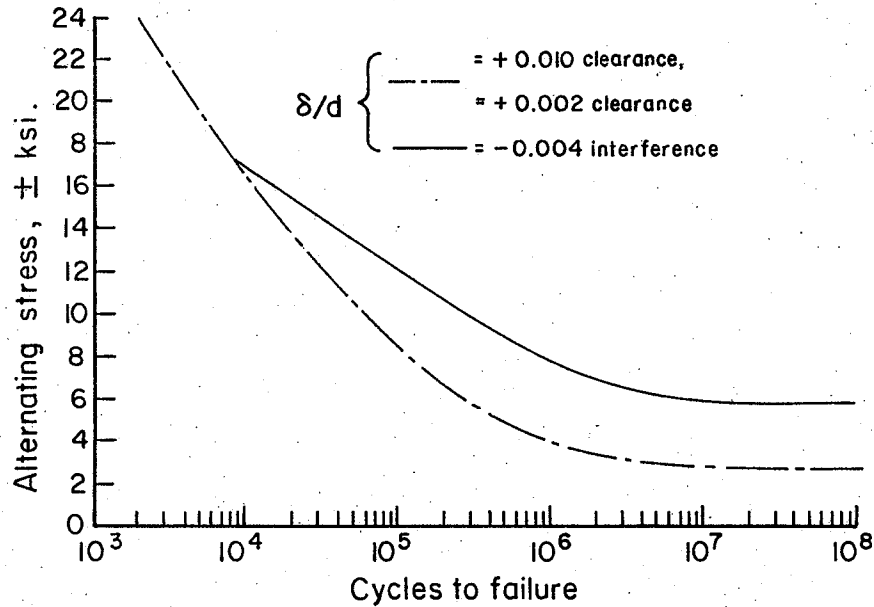


Figure 2.5 Effect of Interference on Fatigue Strength of Aluminum Alloy Lugs (8). Material: 24S-T Alclad Sheet. Dimensions: $d = 0.394$, $D = 1.18$ inch

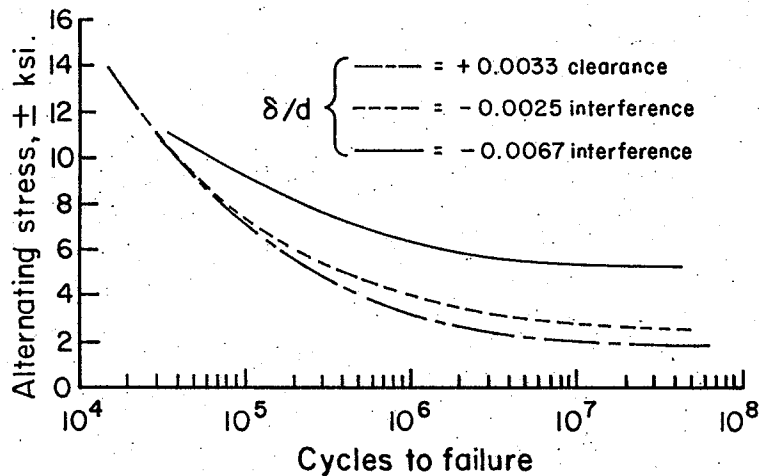


Figure 2.6 Effect of Interference on Fatigue Strength of Aluminum Lugs (8). All Conditions as in Figure 2.5 except $d = 0.236$ inch

high interference of 0.007 inch per inch with which the load-carrying capacity for a service life of 10^6 cycles was increased by about 300 percent. In addition, with reference to Figure 2.7, the author suggested that the best interference may vary with the design life (or loading) of the joint.

Smith (10) also arrived at the conclusion that one and only one amount of interference is optimum for a given loading of a component. Zero-to-tension fatigue tests on the effect of pressed-in bushings of hardened steel on the fatigue life of semicircular-ended lugs of 7075-T6 aluminum alloy indicated an optimum interference of 0.006 inch per inch of hole diameter for which a fatigue life of over a million cycles was achieved as compared to 34,500 cycles with no interference and for the same loading. The average fatigue lives with interference values of 0.004 and 0.008 inch per inch were significantly greater than the average obtained with no interference but were less than the average achieved using an interference of 0.006 inch per inch. Smith (11) added further support to the concept of an optimum interference for a given loading of a component by developing the life versus interference curve in Figure 2.8 for small 0.10-inch-thick lugs of 7075-T6 aluminum alloy tested at approximately 6.0 ± 6.0 ksi gross area stress and using taper pins to provide known amounts of interference.

Mittenbergs and Beall (12) showed that with increasing interference, the fatigue strength of SAE 4340 steel, pin-loaded lugs subjected to a combined loading consisting of a steady tension component and an

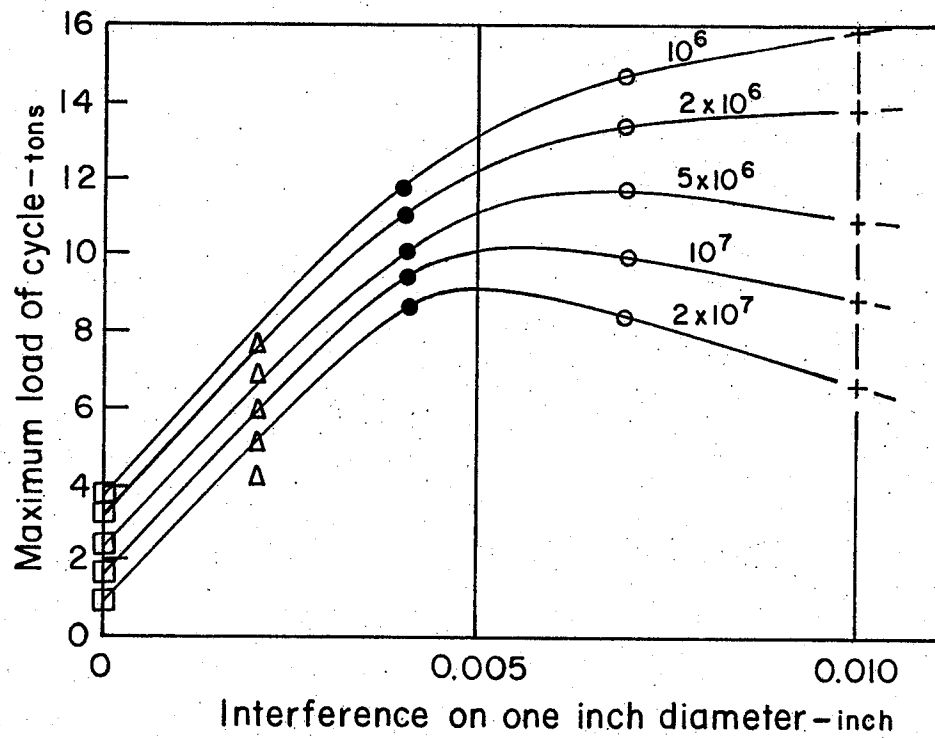


Figure 2.7 Effect of Interference on Fatigue Strength of Aluminum Alloy Lugs (9)