STUDY OF STRESS CONCENTRATION ON THE

FATIGUE LIFE OF MAGNESIUM ALLOYS

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SUMMARY

Fatigue studies of the four common magnesium sheet alloys with respect to various stress concentrations are presented in this investigation. Stress concentrations were created by: (1) holes in the specimens normal to the surface of the sheet, and (2) roughening of the surface by Aloxite Finishing Cloth with scratches perpendicular to the direction of normal stress. All specimens were subjected to completely reversed bending of stress parallel to the grain. Tensile tests were made on specimens taken from the same sheet from which fatigue specimens were made to check the physical properties of the different metals. The effect of rivets in material subjected to fatigue stress is also studied in this investigation.

From the results obtained, stress concentration factors in fatigue imparted by the various stress concentrations were calculated and compared with the theoretical by means of a sensitivity index.

INTRODUCTION

The structural requirements usually desired of light metals is such that their service performance is frequently

determined by their fatigue characteristics. The fatigue
strength of a metal not only depends upon the stress distri-
bution in the critical sections and on the fatigue strength
of the material itself, but it also depends upon the capacity
of the material to withstand concentrations of stress. Ex-
perience has shown that service failures usually occur at stress
concentrations which are associated with the general design,
the methods of joining, and the conditions of surface finish.
Service experience has shown that in magnesium castings, high-
ly stressed regions should have a stress concentration factor
maintained below 1.30 for proper design conditions. In such
regions as the vicinity of screw threads and bolt and stud
holes where severe stress concentrations may exist when loads
are applied, the stress concentration factor may be as high
as 5. The nominal stress is maintained at a low level in this
case by means of thicker sections and bosses. Wrought metal
structures occasionally have stress concentrations as high as
9 at joints, and in order to reduce the maximum nominal stress,
local reinforcements must be used. In his study on notch sen-
sitivity, Found[1] compared fatigue data between magnesium and
aluminum alloys at stress concentration factors above 2. Bond[2]

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[1]G. H. Found, "Found on Notch Sensitivity in Fatigue
Loading of Some Magnesium-Base and Aluminum-Base Alloys", Pro-
ceedings of the American Society for Testing Materials, Vol.
46, 1946. p. 715.

[2]A. C. Bond, "Fatigue Studies of 24S-T and 24S-T Alclad
Sheet with Various Surface Conditions", (unpublished Master's
Thesis, Georgia Institute of Technology, Atlanta, Georgia, 1948),
p. 24.

concluded that stress concentration factors should be applied to design loads in computing margins of safety.

Hence we can see the importance of studying stress concentrations and their effect on materials in fatigue. The author has attempted in this investigation to obtain fatigue data that may prove beneficial to the designer in making more accurate calculations in regard to several types of stress concentrations in four of the more prominent magnesium sheet alloys: Ma, Mh, FS-la, and FS-lh.

STRESS CONCENTRATION THEORY

The distribution of stress across an ordinary tensile test specimen is normally uniform and is equal to the load applied divided by the area of the cross section. If a small hole is drilled through the center of the test specimen, it might seem possible to compute the nominal stress by again dividing the load by the net cross sectional area. However, such is not the case. Both the theory of elasticity[3] and measurements by photoelastic means clearly show that the stress is not uniformly distributed, but instead varies across the section. The maximum stress is located at the edge of the hole and is several times the nominal stress. Similarly, a small hole drilled transversely (normal to the neutral surface) in a specimen subjected to bending will cause a high localized

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[3]S. Timoshenko, Theory of Elasticity, 1st. Edition, (New York and London: McGraw-Hill Book Company, Inc., 1934) pp. 75-82.

stress at the edge of the hole which is greater than the nominal stress obtained from the flexure formula,

$$f = \frac{M\,y}{I}$$

where f = nominal stress in pounds per square inch

M = bending moment in inch pounds

y = distance from the neutral axis to the outer edge of the hole in inches

I = moment of inertia of the section about its neutral axis in inches[4].

The ratio of this actual maximum stress at the hole to the nominal stress at the hole is known as the stress concentration factor. In fatigue studies, then, the effective stress concentration factor (or the strength reduction factor), K_f, as measured by fatigue tests is defined herein as:

$$K_f = \frac{\text{Maximum nominal stress of the unnotched specimen}}{\text{Maximum nominal stress of the notched specimen}}$$

where both of the nominal stresses are based on the net section of the test specimen and are determined at the same fatigue lifetime.

Stress concentrations, however, are not limited just to holes. Instead a considerable disturbance in stress distribution results where there is an abrupt change in the cross section of a material whether due to a hole, scratch, joint, or other form of notch. In each case the maximum stresses encountered at the discontinuity are much greater than would be indicated by the change in the cross sectional area.

The high or peak stresses due to any of the above stress raisers are usually confined to a small region. Take, for example, a small transverse hole located in a wide plate subjected to tension. The stress concentration factor is 3.0 at the edge of the hole, but at a distance of twice the radius of the hole the factor is reduced to 1.22. And at a distance of three times the radius the stress concentration factor is only 1.075. From this information given by Neugebauer[4] it can be seen that the greatest effect of the stress peak is felt by a comparatively few grains around the boundary of the hole. It has been proven that highly stressed material will act more like an isotropic material when the stress gradient per grain is small than when the stress gradient per grain is large. It must be realized that this stress gradient per grain will not only depend upon the size of the specimen and the grain size, but also on the type of stress concentration encountered. For some types of stress raisers the stress concentration is extremely localized, but for others the effect is much more widely felt.

The effective stress concentration factor in fatigue as previously defined is therefore seen to be effected by at least four variables: material, geometric shape, grain size, and the stress gradient. From a study of these factors, Peterson and Wahl[5] made several observations. Those pertiment to our

[4]G. H. Neugebauer, "Stress Concentration Factors and Their Effects on Design-ll, Product Engineering, Vol. 14, 1943. pp. 168-172.

subject matter were:

(1) In some cases the stress concentration factors in fatigue were found to be in quite close agreement with the theoretical stress concentration factors.

(2) Effective stress concentration factors in fatigue determined for small specimens should not be applied to the design of machine parts without regard to size. A reduction in the size of the specimens relative to the size of the hole resulted in a decrease in the stress concentration factor. For very small specimens the fatigue stress concentration factor is nearly unity.

Many investigators, concerned with stress concentration, have devised both theoretical and special experimental methods for determining stress concentration factors for numerous types of discontinuities. Howland[6], for example, arrived at an analytical solution for the theoretical stress concentration factor of a circular hole in a strip under tension, and was in fairly close agreement with Coker[7]. Numerous investigators have even attempted with photoelastic studies to arrive at a

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[5]R. E. Peterson and A. M. Wahl, "Two and Three Dimensional Cases of Stress Concentration and Comparison with Fatigue Tests", American Society for Mechanical Engineers, Transactions, March, 1936. pp. A-15-22.

[6]R. C. J. Howland, "On the Stresses in the Neighborhood of a Circular Hole in a Strip under Tension", Phil. Transactions of the Royal Society of London, A 229, 1929. p. 4.9.

[7]E. G. Coker, "The Effects of Holes and Semi-Circular Notches on the Distribution of Stress in Tension Members", Proceedings of the Physics Society, 1912-1913. p. 95.

definite solution to the problem. Wahl and Beeuwkes[8] arrived at an emperical equation for the stress concentration factor which yielded results that agreed approximately with their test data. This equation,

$$K_t = 3 - 3.13 \ (d/w) + 3.76 \ (d/w)^2 - 1.71 \ (d/w)^3$$

where d = diameter of the hole

w = width of the plate

was used in determining the theoretical stress concentration factor used in this paper for transverse holes, and was found to agree with the value obtained from the method outlined by Neugebauer[9].

No such method is feasible in the case of scratches since there is no uniformity in their configuration. However, from previous results, and since, in all cases investigated, the scratched specimens failed at lower numbers of cycles than did the plain specimens at the same stress, it is obvious that there is a definite concentration of stresses at the scratches. For the purpose of setting up a sensitivity index, as later explained, a theoretical stress concentration factor of 2.0 was assumed for the scratched specimens.

By means of the theoretical stress concentration factor,

[8]A. M. Wahl and R. Beeuwkes, "Stress Concentration Produced by Holes and Notches", American Society of Mechanical Engineers, Transactions, (The Mack Printing Co., Easton, Pa.) Vol. 56, 1934. p. 617.

[9]G. H. Neugebauer, "Stress Concentration Factors and Their Effect on Design", Product Engineering, Vol. 14, 1943. pp. 82-86.

which depends upon the shape of the material and the type of stress concentration, the maximum stress concentration at the base of the notch can be expressed as a multiple of the calculated stress in the section without a discontinuity, or nominal stress. The maximum stress concentration equals the product of the stress concentration factor and the nominal stress. However, notch fatigue tests with notches of known stress concentration factors indicate that the maximum stress concentration is not fully effective. Instead, the ratio between the fatigue strength of unnotched specimens and the nominal fatigue strength of the notched specimens indicates an effective stress concentration factor which is smaller than the theoretical stress concentration factor. By means of a sensitivity index it is possible to express the effect of a localized stress peak in reducing the fatigue strength of a metal as compared to what might be expected theoretically.

In order to have a concrete means by which we can actually compare results of materials of various strengths and different forms on the same basis, Peterson[10] defined this sensitivity index as follows:

$$q = \frac{K_f - 1}{K_t - 1}$$

where q = sensitivity index

[10]R. E. Peterson, "Methods of Correlating Data from Fatigue Tests of Stress Concentration Specimens", Stephen Timoshenko 60th. Anniversary Volume, (Macmillan and Co. Inc.: New York), 1938.

K_f = maximum effective stress concentration factor in fatigue

K_t = theoretical stress concentration factor.

By means of this equation we are able to scale the sensitivity of different metals due to a particular type of discontinuity. For example, if there is no fatigue strength reduction, then K_f will be equal to unity and the sensitivity index, q, will be zero. On the other hand, if K_f should equal the theoretical stress concentration factor, K_t, then q will be equal to unity. Therefore all test data can be tabulated in accordance with a scale varying from q equal to zero (no reduction of fatigue strength) to q equal to unity (full theoretical effect).

This concept may seem quite cumbersome at first sight, but without it or something similar, Peterson noted, it would be impossible to obtain an actual comparison of metals and interpretation of results of materials of various strengths and different forms on the same individual basis.

Although the manner in which the stress concentration factor and the sensitivity index exert an influence on the nominal fatigue strength is clear, use of the sensitivity index as a calculating factor is limited. For instance, it can be used in cases where notch shapes or stress concentration factors do not greatly differ, and where it is especially necessary to make allowances for differences in the stress concentration factors of the same notch shape under different

types of stress. The main significance, then is in its use,
not as a calculation factor but as an index of the compara-
tive notch sensitivity of materials, a property which is of
great importance in practice.

MATERIAL

The four materials used in this investigation were the
more familiar magnesium sheet alloys, with the following Dow-
metal designations: Ma, Mh, FS-la, and FS-lh, where the fi-
nal letter specifies annealed, a, or hard rolled, h. Actually,
then, only two alloys were tested, but each with two cold worked
conditions. However, in order to avoid any perplexity, each
will be designated a separate material. All four materials
were in the form of sheet and only one standard thickness,
0.064 inch, was used for the tests. The nominal chemical com-
position of the FS-1 alloys is as follows: 3.0 percent alum-
inum, 1.0 percent zinc, and the balance magnesium. The nom-
inal chemical composition of the M alloys is 1.2 percent man-
ganese and the remainder magnesium. The FS-la sheet material
was shipped with the chrome pickle treatment applied. How-
ever, as advised by The Dow Chemical Company, this treatment
was removed by an abrasive.

Representative Stress-Strain curves of the four alloys
used are presented in Figures 7, 8, 9, and 10. These are the
average values resulting from three tensile tests conducted
on each of the four sheets of material. The specimens used

were the standard American Society of Testing Materials' Tension Test Specimen, described by Davis, Troxell and Wiskocil[11] in their book on materials testing. The tests were conducted on a Riehle Universal Hydraulic Testing Machine, a Huggenberger type extensometer being used to measure the elongations. The mechanical properties of yield point stress, ultimate stress, and modulus of elasticity thus derived of each alloy is tabulated in Table 1. These values were compared with those presented in both the ANC-5[12] and the manual "Magnesium Alloys and Products"[13] and were found to agree closely with the exception of the modulus of elasticity which the author found most difficult to determine from the curves with any large degree of accuracy.

THE FATIGUE TESTING MACHINE

The machine with which the tests described herein were conducted was a Sonntag Flexure Fatigue Machine, Model SF-2. Three photographs, Figures 1, 2, and 3, show a sample loaded in the machine and indicate clearly the main features of the

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[11]H. E. Davis, G. E. Troxell and C. T. Wiskocil, The Testing and Inspection of Engineering Materials (New York: McGraw-Hill Book Company, Inc., 1941), p. 80.

[12]Anonymous, "Strength of Aircraft Elements", ANC-5, Army-Navy-Civil Committee on Aircraft Design Criteria, Revised Edition, December 1942, Amendment-2, August 1946.

[13]Anonymous, "Magnesium Alloys and Products" (Booklet presented by The Dow Chemical Company, Magnesium Division, Midland, Michigan, 1950), p. 24-25.

loading. These photographs will be referred to throughout the following discussion on the operation of the machine.

The Sonntag Machine is a completely reversed, repeated force fatigue machine which uses a rotating eccentric mass, A, to generate the force. The eccentricity of the mass being adjustable to give a force output as shown on the scale, B, and remains a constant for any fixed value of eccentricity. The force is transmitted through rod, C, to load yoke, D. The side forces of the eccentric are absorbed by pivot rod, C, which limits the travel of the rod in the vertical direction. The specimen is clamped in the load yoke by means of the pivot bar, F, clamp bar, G, and clamping bolts, H. Adjustable pedestal, I, rigidly holds the fixed end of the specimen, which is clamped by bar, J, and bolts, K.

As previously noted, the force remains a constant for any fixed value of mass eccentricity. A system of inertia compensation is used in order to keep the force applied on the specimen constant irrespective of the amplitude. The function of this compensation is to absorb all inertia forces in the vibrating system in order that the eccentric force alone acts on the specimen. A mathematical proof of the method is given in the appendix of the operating manual of the machine[14].

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[14]Anonymous, "Instructions for Installation, Operation and Maintenance of Flexure Fatigue Testing Machine, Model SF-2, Serial No. 472875". Manual furnished by Sonntag Scientific Corporation, Greenwich, Connecticutt, prepared July 1947, Appendix Print No. 90273-S.

However, simply stated, a spring, the tapered drive shaft, N, is used whose deflection constant is equal to the inertia forces of the vibrating system. As the inertia forces increase with the deflection of the system, a compensation is made by the spring reaction which cancels the inertia forces. This leaves only the eccentric force or a repeated force of constant value applied on the specimen. Since the whole system must be in resonance as shown in the mathematical derivation for this condition to hold, it is only valid for a given frequency and a given mass system. A $\frac{1}{4}$ horsepower synchronous motor operating at a constant speed of 1800 revolutions per minute maintains this constant frequency for the system. Variable poise weights, P, are also provided to adjust for differences in the mass of the system when different weight specimens are used.

Because of the important condition that the mass of the system be kept constant, it was necessary to calculate the poise setting in order that the machine be tuned to resonance. This setting was determined by calculating the effective weight of the specimen,

$$W_e = 0.385 \times d \times t\,[15]$$

where W_e = effective weight of the specimen in pounds

    d = density in pounds per cubic inch

    t = thickness of the material in inches

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[15] Ibid., p. 90450-S, sheet 3.

and referring this to graph No. 90452-s[16]. Graph No. 90452-s is a curve which was determined at the factory for the purpose of tuning this particular machine to resonance at various values of the effective weight.

The last adjustment to be made is for the amount of force to be applied to give the desired stress. Graph No. 90446-s[17] is provided as a calibration curve of specimen stress per pound of force for various thicknesses of the specimen. As noted by Bond[18] and Duchacek[19] this curve is an adaptation of the beam formula,

$$f = \frac{M\,y}{I}$$

where f = normal unit stress in pounds per square inch

    M = bending moment on the cross-section of the specimen in inch pounds

    y = distance parallel to the plane of bending between the point under consideration and the neutral axis, or one-half the thickness in inches for maximum stress, which occurs at the surface

    I = moment of inertia of the section about its neutral axis in inches[4].

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[16]Ibid., graph No. 90452-s.

[17]Ibid., graph No. 90446-s.

[18]Bond, op. cit., p. 8.

[19]H. Duchacek, "A Study of the Effect of Thickness on Fatigue Strength of 24S-T3 Aluminum Alloy Sheet" (unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 1948), p. 10.

This formula may be modified to include the force of the eccentric mass by letting

$$M = P \times L$$

where P = force of the eccentric mass in pounds

      L = the distance in inches from the load yoke to the point under consideration on the test section of the specimen.

The graph proved to be very useful in that it eliminated the individual calculations each time the load was varied. By knowing the desired stress, it was only necessary to divide the specimen stress per pound of force for a given thickness into the desired stress to obtain the setting on the eccentric.

Important considerations to heed in the running of any test specimen include: (1) correct tuning of the mass or the force exerted on the specimen will be some value other than that shown on the eccentric, (2) determining and adjusting the values of the loads to be applied, and (3) determining the weakest section or point of minimum thickness of the test specimen.

THE FATIGUE SPECIMENS

A plan form of the specimens used for the fatigue tests reported here is shown in Figure 4, giving complete dimensions and mounting details. As may be deduced from the layout of the specimen, it incorporates a beam with constant bending stress as the test section. Since the applied bending stress is con-

stant at any point on the test section between the two points where the radii become tangent to the straight sides, failure due to fatigue stressing may be expected to occur at any section between the two above extremeties. This expectation was realized as can be seen from Figure 6 which shows a fracture at a random location within the test section.

Preparation: In preparing the specimens it was necessary at all times during the handling of the material to be extremely careful not to scratch or mar the surface or edges. A high speed router guided by a template was used to cut the specimens to a uniform shape. The tool marks in the edges were removed with a light abrasive and then polished with crocus cloth.

In order to maintain equal surface conditions, each specimen was polished in the same manner. First the abrasive, Behr-Manning speed-wet durite 600A, was placed on a flat, smooth board and the specimen was held firmly by hand and moved in the direction of the grain across the paper. Micrometer readings of the thickness were frequently taken until this dimension was within one thousandth of the desired test thickness, 0.064 inches. The abrasive was then replaced by crocus cloth and the same procedure for polishing was followed. The specimen was then lightly buffed on both sides to clear the test section of any further remaining scratches. Emphasis must be placed on the fact that all polishing and buffing was done in the direction of the grain of the specimen.

It is worthy of note that the stock of several of the

alloys shipped, namely Mh and FS-1h, proved to be between four and six thousandths of an inch over the desired thickness. In such cases, a coarser abrasive was applied to the specimens before the aforementioned. On the other hand, the alloy FS-1a was found to be slightly less than the required thickness. This not only required careful and light polishing, but a correction in the setting of the eccentric mass. In any case, after the specimen was polished, great care was taken to prevent any further treatment that could effect the mechanical properties of the material.

Grain Direction: All specimens were cut with the centerline parallel to the direction of rolling of the sheet in order to give uniformity of this parameter. Although Brick and Phillips[20] in their investigation of the effect of grain direction on 24S-T and 24S-T Alclad arrived at the conclusion that a marked variation existed in the results of the two, Found[21] did not find this to be the case with magnesium alloys. Instead, it was found that the results of tests on plain and notched specimens stressed transversely to the rolling direction were practically identical to those results obtained when the specimens were stressed in the direction of the rolling. He estimated the possible experimental error to be about ±1000 pounds per square inch for his tests. In any event, the dir-

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[20]R. M. Brick and A. Phillips, "Fatigue and Damping Studies of Aircraft Sheet Materials", American Society for Metals, Transactions, 29:441, June 1941.

[21]Found, op. cit., p. 715.

ection of bending parallel to the direction of rolling was selected for investigation as it was necessary to limit the study to only one grain direction.

Notches: Two different types of notches, or stress concentrations, were used in these fatigue tests, namely, specimens with surface scratches and specimens with a transverse hole located in the test section.

Scratches: The surface of each specimen was scratched with Number 180 Aloxite Finishing Cloth. In his studies of the effect of various abrasives on the fatigue life of 24S-T and 24S-T Alclad alloys, Bond[22] concluded that surface scratches definitely reduced the flexure fatigue strength of the two aluminum alloys tested, and that the greater the depth of the surface scratch, the greater the reduction. The abrasive selected in this study was about the median roughness of those he used in his tests.

Both sides of the specimens were uniformly roughened over the entire test section with the abrasive, applying the force by hand. In order to obtain the greatest reductions in fatigue strength, the scratches were made transverse to the direction of stress. Figure 6 shows an unbroken and broken, scratched specimen.

Horger[23] states that surface finish marks in planes

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[22]Bond, op. cit., p. 24.

[23]O. J. Horger, "Fatigue Strength of Members Influenced by Surface Conditions", Product Engineering, 11:492, December 1940.

transverse to the direction of stress have detrimental effects on the fatigue strength. He also cites that service perform- ance of springs and axles are prominent examples where longi- tudinal cracks have been found to have little or no influence on the bending fatigue strength. It can easily be seen that transverse scratches have a considerably more detrimental effect on fatigue life than do longitudinal scratches because, in bend- ing, the normal stresses are perpendicular to the transverse scratches. As any type of discontinuity, such as a scratch, nick, or hole provides nuclei for stress concentrations, the entire width described by the transverse scratches tends to upset or retard the flow of normal stresses and hence stress concentrations exist all along the transverse scratches. In the case of longitudinal scratches, the effect is relatively small, as the scratches are parallel to the normal stresses and hence do not tend to retard the flow to such a degree as do the transverse scratches.

Since the entire test section of each specimen was thoroughly roughened by the finishing cloth, a great number of scratches were imparted in a small area. Therefore the scratches were either lying side by side or overlapping. For this reason, it can be assumed that the stress concentration factors obtained from the tests are not the highest possible. An important fact concerning stress concentration as explained by Roark[24] is that a single isolated notch has a worse effect

[24]R. J. Roark, Formulas for Stress and Strain, Second Edition (New York: McGraw-Hill Book Company, Inc.,1943)p. 32.

than do a number of similar stress raisers placed close to-
gether. In other words, by placing one stress raiser closely
adjacent to another, the stresses on one would tend to relieve,
to a certain degree, the stresses on the other, and vice versa.
Thus it is reasonable to say that a single scratch will pro-
vide stress concentration factors of greater magnitude than
those presented in this paper. A theoretical stress concen-
tration factor for the scratched specimens was not obtained
because of the complexity of the problem of measuring the depth
of the scratches, and because of the manner in which the scrat-
ches were applied. However, in order to obtain a sensitivity
index, a theoretical factor of 2.0 was assumed for scratched
specimens.

Transverse Hole: Fatigue tests were run with
the test specimens containing a single drilled hole in the
test section. It can be seen from Figure 6 that the hole is
located on the longitudinal centerline of the specimen. The
transverse hole is 1/16 of an inch in diameter and located in
the test section where the width of the plate is 0.5 inches.
The location of the hole yields a geometric or theoretical
stress concentration factor of 2.66 by the methods described
by Neugebauer[25] and Wahl[26]. In all cases, the holes were drill-
ed holes. That is, they were neither reamed nor polished since

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[25]Neugebauer, op. cit., p. 83.

[26]Wahl, op. cit., p. 617.

it was desired to evaluate their effect under conditions app-
roximating service. As was the case with the scratched speci-
mens, it was found by Roark[27] that a single isolated hole has
a worse effect than do a number of similar holes placed close
together on a test specimen. However, making such tests was
beyond the scope of this paper.

One complete test run was made on specimens with alum-
inum brazier head and countersunk rivets driven into the tran-
sverse hole. This run was made to verify several facts, later
mentioned, on the effect of riveted specimens in fatigue and
not to yield extensive results. Figure 6 shows a riveted
specimen both before and after fracture.

<center>TEST PROCEDURE</center>

The specimen is clamped in the machine in a horizontal
position with the centerline of the specimen perpendicular to
the face of the pedistal as shown in Figures 3 and 4. One
end of the specimen is rigidly fixed and the other is clamped
in the load yoke. The desired stress is obtained by setting
the calculated eccentric mass location as explained before.
The counter is set to zero and the test is begun. When fail-
ure occurs, the limit switch automatically stops the motor,
at which time the number of cycles until failure is read from
the counter. Another specimen is then placed in the machine
and the same procedure is followed.

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[27]Roark, op. cit., p. 32.

The tests for each particular curve were begun at the high values of stress and were decreased in increments of five-hundred to two thousand pounds per square inch depending upon the overall fatigue range. This method enabled the operator, from observing the general trend of the fatigue curve, to predict with reasonable accuracy the life of the specimen at a given lower stress.

The maximum stresses for all tests were determined as those necessary to give only a few thousand cycles of reversed stress. However, in all cases, these stresses were never allowed to exceed the yield point of the particular material. The specimens stressed in the lower range were generally loaded to fail within a lifetime of ten million cycles of stress because of the time element involved. Whenever a specimen was removed from the machine before actual failure had occured, that particular point was indicated on the plots with the conventional horizontal arrow at the point where the test was discontinued.

The curves of the specimens with no stress concentration were first run in order to determine the "par value" and also to serve as a check in the correct usage of the machine by comparison with other data. Values from these curves agreed with fair accuracy with those reported by ANC-5[28] and Found[29].

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[28]Anonymous, op. cit., p. 56.

[29]Found, op. cit., p. 715.

Preceeding operators of the fatigue machine had noted that results from this particular machine were approximately eight percent lower than values formerly obtained on the same metal. This was due to the router jig which, through extensive usage, was found to have a cross-sectional area slightly less than the requirements. Since the fatigue stress of these specimens was based upon the specified cross-section, a higher stress than the calculated value was actually applied to the test section. However, since the scope of this paper was to determine the effect of stress concentration on a comparison basis, no attempt was made to correct this decrement stress.

Next, the tests of the specimens with the transverse hole were run to determine their fatigue life. The alloys were then tested with riveted sections, but since this type of stress concentration is believed to have the same detrimental effect on all alloys, only one complete test run was made.

Finally, the scratched specimens were tested in the fatigue machine to determine the effect of a definite surface condition on the fatigue life of the four alloys.

DISCUSSION OF RESULTS

The results of all the fatigue tests run were plotted in the form of S-N diagrams(i. e. stress versus number of cycles). In keeping with the conventional methods of presenting these fatigue results, semi-logarithmic paper was used for

plotting the results. A summary of the fatigue strengths for each material is shown in Tables 3 and 4 at eight different fatigue lifetimes. The corresponding effective stress concentration factors in fatigue taken from the respective curves are also listed.

Fatigue Results of Ma: Figures 11 and 12 show the results of fatigue tests on Ma sheet of specimens with a transverse hole and scratched specimens, respectively. The experimental points obtained are clearly indicated on the graphs and the curves are faired through them. In addition, the fatigue curve of the plain specimens is included on each graph for comparison purposes.

From a consideration of the fatigue curves it is immediately seen that there is a definite tendency in each case toward a significant flattening out of the curves in the vicinity of 10^6 to 10^7 cycles. This is especially true in the case of the scratched specimens. The reduction in the fatigue strength of the plain specimens during the long life period, 10^6 to 10^7 cycles, is from 8,600 to 8,200 pounds per square inch, or a decrease of 400 psi. The long life period of the specimens with a transverse hole varies from 5,700 to 5,000 pounds per square inch, or a decrease of 700 psi. This lesser tendency of the latter curve to flatten out during this range will be found to be the case in most of the tests run in this paper. However, the scratched specimens varied only 250 psi between the limits of the long life period, which, as stated above, shows the greatest tendency towards approaching an endurance

limit.

The terms "short life", "moderate life", and "long life" are used throughout this discussion to differentiate between positions of the fatigue curve. The short life period is between 5×10^3 and 10^5 cycles, and the moderate life is within the range of 10^5 and 10^6 cycles. The last period is from 10^6 cycles and greater.

Figure 20 shows the variation of the effective stress concentration factor in fatigue of the two types of specimens with the number of cycles. The scratched specimens show a distinct linear variation of the stress concentration factor over the complete lifetime. This curve, steadily decreasing with the number of cycles is contrary to that illustrating the change of the stress concentration factor due to a transverse hole. The latter, almost a straight line variation, increases from a stress concentration factor of 1.24 at the earliest lifetime obtained, 5×10^3 cycles, to a factor of 1.64 at the maximum lifetime.

The overall picture shows that the fatigue strength of the Ma alloy is more severely affected by a stress concentration due to a transverse hole than a stress concentration caused by scratches. The average effective stress concentration factor in fatigue of the specimens with a transverse hole was 1.43, and that of the scratched specimens was found to be 1.09.

Fatigue Results of Mh: Figures 13 and 14 show the results of fatigue tests on Mh sheet of specimens with a trans-

verse hole and specimens subjected to scratches, respectively.
Here, likewise, the experimental points are indicated on the
graphs and the curves are faired through them. Again the curve
of the plain specimens is included with each graph in order
to illustrate the reduction in fatigue strength due to the
types of stress concentrations.

The fatigue curves of this alloy do not show a definite
tendency towards an endurance limit with the possible except-
ion of the scratched specimens. Whereas the long life stress
of plain specimens varies from 11,750 to 10,600 pounds per
square inch, the scratched specimens in this range only de-
creased 700 psi. On the other hand, the specimens with a
transverse hole again showed less tendency to flatten out as
there was a decrement of 1,100 pounds per square inch within
their long life period.

Figure 21 shows the variation of the effective stress
concentration factors in fatigue of the two types of specimens
with the number of cycles. The scratched specimens, rather
than showing a linear decrease in their factors, demonstrated
that this type of stress concentration yielded practically a
constant effect on the fatigue life. As can be seen from this
curve, the stress concentration factor increases from 1.11 at
the earliest computed lifetime to a maximum of 1.18 at the end
of the short life period, 10^5 cycles. Throughout the moderate
lifetime and the long life range, however, the curve showed a
negative slope.

The effect of a transverse hole as a stress concentration is readily seen from the same curve. Beginning at a value of 1.21 as a stress concentration factor at the earliest lifetime, this type of stress raiser showed a rapid increase from this value during the moderate life range. During the long life period the curve attains a "rounding off" effect. However, the maximum factor occurs at 10^7 cycles and is 2.12. With a stress concentration factor of 3, the stress at the edge of the hole is still high, consequently this contributes to a resulting shorter life for any given nominal stress.

Again, the overall picture shows that the fatigue strength of the Mh alloy is more severely affected by a stress concentration due to a transverse hole than a stress raiser caused by scratches. However, in this case, the effect of the scratches is only slight as compared to the large effect produced by specimens with a single transverse hole located in their test section. The average effective stress concentration factor in fatigue of the scratched specimens was 1.14, whereas that due to a transverse hole was as high as 1.65.

Fatigue Results of FS-la: Figures 15 and 16 show the results of fatigue tests on FS-la sheet of specimens with a transverse hole and specimens subjected to scratching. The experimental points are indicated on the graphs and the curves are faired through them. The curve of the plain specimens is also included with each graph for purposes of comparison.

It is evident from Figure 15 that specimens with a trans-

verse hole have a marked detrimental effect of the fatigue strength of this alloy as compared with specimens with no stress raiser present. The curve illustrating the trend of fatigue tested specimens with this stress concentration although not demonstrating any definite endurance limit, does have a greater tendency to flatten out than the curve for plain specimens. The long life period of the latter begins at a fatigue strength of 13,800 psi, and ends at 12,800 psi, or a decrease of 1000 pounds per square inch. However, for the specimens with a transverse hole, this lifetime range is between 10,300 and 9,500 psi, or a decrease of 800 pounds per square inch.

Figure 16 compiles the fatigue test data of the scratched specimens and compares it with the results from the plain specimens. These curves show that scratches have a slight effect on the fatigue strength of this alloy. It is interesting to note that at long lifetimes, the two curves tend to coincide. For example, at 10^7 cycles the fatigue strength of the plain specimens was found to be at 12,800 psi, whereas that for the scratched specimens was 12,750 pounds per square inch. Not enough data was taken, however, to be conclusive.

Figure 22 shows the variation of the effective stress concentration factors in fatigue of the two types of specimens with the number of cycles. Since the fatigue strengths of the scratched and plain specimens were found to be almost equal at the longest lifetime tested, the calculated stress concen-

tration factor at that point was practically equal to unity. Or, as shown in this curve, as the lifetime increased, the effective stress concentration factor of the scratched specimens decreased from a maximum of 1.10 at 5×10^4 cycles to 1.01 at 10^7 cycles. The stress concentration factors for the specimens with a transverse hole did not prove to be large as the maximum factor, occuring at 5×10^6 cycles, was only 1.35. The curve followed the usual pattern for this type of stress concentration in that it increased from the short lifetime where at 5×10^3 cycles its stress concentration factor was 1.21.

The fatigue strength of the FS-la alloy is decreased, but not to any large degree, by both of the stress raisers. The transverse hole is slightly more detrimental to the life of the material than scratching. The average effective stress concentration factor in fatigue of the former being 1.31 and that due to the latter was 1.07.

Fatigue Results of FS-lh: Figures 17 and 18 show the results of fatigue tests on FS-lh sheet of specimens with a transverse hole and scratched specimens, respectively. The experimental points obtained are clearly indicated on the graphs and the curves are faired through them. In addition, the fatigue curve of the plain specimens is included on each graph for purposes of comparison.

The fatigue curves show that there is a definite tendency for the curves to flatten out. This particular alloy

differed from the others tested in that during the short life period a rapid linear depreciation in fatigue strength occured. However, after that particular lifetime, a sudden change in the slope of the curve took place, and it too, was drawn as a straight line. This sudden change phenomenon occured in the vicinity of 5×10^4 cycles. Contrary to the practice of some investigators, this sudden change was faired into the curve instead of letting the two straight lines intersect at that point. When the transverse hole was tested as a stress raiser, this same phenomenon occured even though the fatigue life at each stress setting was greatly reduced from that obtained from the plain specimens. The scratched specimens, although illustrating the same effect, did not have a noticeable change in slope until the moderate lifetime had begun.

Figure 23 shows the variation of the effective stress concentration factor in fatigue of the two types of specimens with the number of cycles. The specimens with a transverse hole exhibited a linear variation of the stress concentration factor with the number of cycles. The curve showing the change of the stress concentration factor with the number of cycles for the scratched specimens varied as follows: a decrease in factors during the short life period, an increase in the values during the moderate lifetime, and a decrease in values during the long life period. This oscillation of the curve can be attributed to the fact that the sudden change in slope of the fatigue curve of the scratched specimens did not occur at the same number of cycles as that of the plain specimens,

but occured at a fatigue life about twenty per cent greater.

The overall picture again shows that the fatigue strength of the FS-1h alloy is more severely effected by a stress concentration due to a transverse hole than a stress raiser caused by scratches. The average effective stress concentration factor in fatigue of the former was 1.52 and that of the scratched specimens was 1.22.

A study of these fatigue curves reveals a certain degree of scatter in the experimental points. However it should be noted that other experimental fatigue results show a similar scatter. In fact, some investigators are of the opinion that fatigue results should be plotted as a band instead of as a single curve. There are several possible reasons for the scatter of points, some being as follows: (1) slight errors in setting the required loading on the eccentric, (2) non-uniformity in the location and preparation of the stress raiser, (3) slight errors in machining and finishing, (4) possible error in reading the calibration curve of the machine, (5) the effect of work hardening, (6) metallurgical differences in the specimens, and (7) the actual nature of the fatigue phenomenon.

As was pointed out in each case, the fatigue curves flattened out frequently in the vicinity of 10^6 to 10^7 cycles. In his investigation of the notch sensitivity in fatigue loading of some magnesium-base and aluminum-base alloys, Found[30]

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[30]Found, op. cit., p. 715.

noted the same results on several magnesium alloys. He also added that the curves for aluminum rarely flattened out at less than 10^8 cycles, which was also cited by Bond[31] and Duchacek[32] in their tests on aluminum alloys.

In all cases, as is to be expected, the annealed alloys were definitely weaker than the alloys which were hard rolled, although the chemical composition of the two were identical. This was proven to be the case not only with the plain specimens, but in the scratched specimens and specimens with the drilled transverse hole as well. Only in the case of fatigue of the M alloy could this possibly be disputed, for with specimens containing the transverse hole, the annealed and hard rolled curves became coincident at the long life period. Although the fatigue strength of the Mh alloy was superior in short life to that of the Ma alloy, both curves coincided at 5×10^6 cycles and remained together from that point to 10^7 cycles. Not enough data was secured to justify the fact that these two alloys with a transverse hole as a stress raiser have equal fatigue strengths beyond this tested range.

By means of the sensitivity index as listed in Table 2 we are able to compare all four alloys on the same basis: their sensitivity to the two types of stress concentrations. From a study of this table we are able to conclude that al-

[31]Bond, op. cit., p. 16.
[32]Duchacek, op. cit., p. 33.

though the fatigue strengths of the hard rolled alloys were superior to those of the annealed class, the former were more susceptible to both types of stress concentrations tested. However, this sensitivity to stress concentrations is not dependent upon the maximum fatigue strength an alloy possesses. For example, the alloy Mh does not rank with the highest alloys in fatigue strength and yet it was the most susceptive alloy when a transverse hole was drilled in its test section. Likewise, FS-la, the least susceptive alloy to stress concentration effects of transverse holes, is definitely of greater fatigue strength than Ma, throughout their complete life ranges.

The susceptibility of an alloy to a certain stress raiser can not be predicted from the knowledge of how that alloy reacts to a different type of stress concentration. This can be easily seen by again considering the alloy Mh. This alloy had the greatest sensitivity to the transverse hole, but it ranks second in sensitivity to scratches, FS-lh in this case being more susceptible. However, after compiling all of the results, the alloy FS-la was least sensitive to both types of stress concentrations tested.

It must be remembered that the values obtained in Table 2 for the sensitivity index have no practical value other than for comparison of materials on the same basis. The formula used in calculating the sensitivity index is to be regarded as a first approximation only.

Effect of Driven Rivets in Transverse Holes: Figure
19 shows the effect on the stress concentration of a rivet
driven in the transverse hole of the specimen, when it is
tested under reversed loading. A 5/32 inch, brazier head,
aluminum alloy rivet was used in this test to determine the
comparison between it and the fatigue test of specimens with
an open transverse hole in the test section. Figure 6 shows
a specimen with a rivet driven as described. It can also be
seen from this figure that fracture of the specimen did not
occur at the cross-section which included the rivet, but in-
stead the fracture occured at a point nearer the load yoke.
All specimens tested yielded the same type of fracture. The
curve shows that the fatigue strengths of these riveted spec-
imens were smaller than those values obtained from the plain
specimens over the complete life range, but larger than those
produced by specimens with a transverse hole alone.

It was first assumed that this type of fracture was
due to an increase in the yield point of the grains immediately
surrounding the rivet as cold working of that portion of the
specimens was visible to the naked eye. Since cold working
of magnesium produces an increase in the yield strength, the
yield strength of the grains surrounding the rivet was greater
than that of the material further away from the rivet. How-
ever, several riveted aluminum specimens, known to be much
less sensitive to cold working, were tested under the same
conditions and the above assumption proved to be doubtful when

they, too, failed in the same manner. The final explanation as to why the specimens did not fail at the rivet may perhaps be the restraint exerted by the rivet head. Because of this restraint, a full reversal of stress may not be taking place in the material adjacent to the rivet during the fatigue tests.

Wilson and Thomas[33] investigated riveted joints under flexural fatigue conditions and arrived at no definite conclusions because of the inconsistency of the results. Instead, only very general statements were made relative to the results on tests of specimens designed to fail in the rivets:

(a) The results of tests in which the shear on the rivets was completely reversed were very inconsistent and indicated that the fatigue strength of rivets under reversed stress may be as high as 30,000 or as low as 15,000 psi in shear on the rivets.

(b) For the joints subjected to complete reversals of stress the life of the rivets was much greater for joints with plates having milled ends in contact so as to take compression by direct bearing than it was for joints for which the ends of the plate were not in contact.

(c) There is some evidence indicating that the ratio of the fatigue strength under reversed stress to the fatigue strength under repeated stress is less for the rivets than it

[33]W. M. Wilson and F. P. Thomas, "Fatigue Tests of Riveted Joints", University of Illinois Engineering Experiment Station Bulletin 302, 1938, 114 pp.

is for the plates of a riveted joint. The results obtained indicate that additional tests are needed to determine, among others, the effect of the tightness of the fit of the rivets and bolts in the holes on the fatigue strength of the rivets and bolts.

They also concluded from fatigue tests of specimens designed to fail in the plates that fatigue tests of small machined and polished specimens have little value as an indication of the fatigue strength of riveted structural members, because, for the latter, rivet holes and the roughness of the rolled surfaces are stress raisers not found in the smaller, more carefully prepared specimens; and the size and shape of the structural specimens make for a greater lack of uniformity in stress distribution than is found in small machined specimens.

Size Effect: That there should be a size effect is not surprising when it is considered that both the theory of elasticity and photoelasticity tests are dealing with homogenious isotropic materials whereas engineering materials are neither homogenious nor isotropic except in a statistical sense. The peak stresses due to stress raisers act over a comparatively small number of grains, particularly in a small specimen, and these grains are not homogenious nor isotropic. For much the same reason it is reasonable to expect that the finer the grain size, the more a specimen of a given size will act like an isotropic material. Thus the value of the effective stress con-

centration factor, K_f, should be closer to the theoretical for a fine grained material than for a coarse grained material.

The effect of size is a very important consideration when applying fatigue data obtained from small specimens to the design of large components. Numerous investigators[34] have noted that the size effect of metal bars and shafts, both notched and unnotched, plays a major role in computing the actual fatigue strengths of metals of commercial size. They found that fatigue strengths obtained as a result of testing small specimens are greater than fatigue strengths obtained as a result of testing large specimens, and that notch sensitivity increases as the size increases. The actual fatigue data of light alloy sheet with respect to size effect is, indeed, meager. Buchmann[35] investigated several light alloys with respect to size effect with the following results:

(a) There was a pronounced drop in the flexural fatigue strength with increasing size, especially in the range of small cross-sectional areas.

(b) Beyond a certain limit, the rate of drop in flexural fatigue strength is only slight; the curves tended asymptotically toward the fatigue strength due to reversed axial loads. The excess strength on reversed flexure over the asymp-

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[34]Battelle Memorial Institute: Prevention of the Failure of Metals Under Repeated Stress, (New York: John Wiley and Sons, Inc., 1941), p. 123.

[35]W. Buchmann, "Influence of Cross-Sectional Area on Fatigue Strength", Engineers Digest, 3:137, March 1945.

totic value is explained by the stabilizing effect of the slightly stressed inner fibers on the highly stressed outer fibers. This effect obviously depends on the stress gradient.

(c) The fatigue strength of unnotched samples due to reversed axial loads is independent of scale factor. With a notched sample, however, there is a stress gradient and consequently, due to the stabilizing effect, there is an influence of size on the fatigue strength.

(d) With fatigue due to alternating torsion there is a distinct influence of the size of the test samples, even when unnotched.

It is therefore obvious from the above findings that the results of this investigation are limited to the design of small components and to sheets of approximately the same gage herein tested.

Application of Data to Design: Fatigue data obtained from the laboratory through the testing of polished specimens are not directly applicable to design, but must be modified to meet the particular design conditions.

The results from these tests on the four most prominent magnesium sheet alloys will be of but limited use for predicting actual stress ranges for safe dynamic loading of parts and assemblies in service. This can be associated with the metallurgical differences between test specimens and the actual parts; and also with the relative effects of surface

finish on the fatigue properties of the specimens as compared to the effect on parts. Often for wrought assemblies, which incorporate sheet, extrusions or forgings, the strength of joints is the determinative fatigue property, while the fatigue properties of the unnotched metal are of secondary importance. Furthermore, in the case of both cast and wrought metal, there is usually a great dissimilarity in the manner in which load is applied to fatigue specimens as compared to full-scale parts under service loading. This accounts for an additional discrepancy between the fatigue properties of the test specimens and the actual parts. How each of the above variables effects the results was beyond the scope of this paper. Suffice it to say that it is recommended that the test data here presented not be used quantitatively for design values, but rather, simply for a qualitative comparison of materials.

CONCLUSIONS

From the foregoing presentation of the results of this investigation the following conclusions are drawn:

1. Surface scratches and holes drilled normal to the neutral plane definitely reduce the flexure fatigue strength of Ma, Mh, FS-1a, and FS-1h sheet material. In all cases the drilled holes are more detrimental to the fatigue properties than the surface scratches.

2. Hard rolled alloys are more sensitive to the stress concentrations than those of the annealed class. Although FS-1h exhibits a greater reduction in fatigue strength than Mh, the latter is more susceptive to drilled holes, especially in the long life region.

3. The effective stress concentration factors in fatigue of the scratched alloys decreased with increasing lifetime; the alloys with a drilled transverse hole shows a definite increase.

4. Riveted specimens reduce the fatigue strength of alloys, but not to the extent of alloys with a transverse hole alone.

5. The stress concentration factors should be applied to design loads in computing margins of safety where reversed or fluctuating stresses occur.

6. Further study should be made on stress concentrations of other types to determine their effect on the fatigue life of materials, and to set up a definite sensitivity index.

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APPENDIX I, Tables

TABLE I

MECHANICAL PROPERTIES OF Ma, Mh, FS-la, AND FS-lh SHEETS
USED IN FATIGUE TESTS

MATERIAL	E, MODULUS OF ELASTICITY, PSI	YIELD STRENGTH, PSI	ULTIMATE STRENGTH, PSI
Ma	5.8×10^6	18,000	30,200
Mh	6.4×10^6	28,200	32,600
FS-la	7.5×10^6	21,600	37,000
FS-lh	6.6×10^6	31,200	41,900

TABLE II

SENSITIVITY INDEX OF SCRATCHED SPECIMENS AND SPECIMENS WITH
TRANSVERSE HOLE FOR Ma, Mh, FS-la, AND FS-lh MAGNESIUM ALLOY
SHEETS

MATERIAL	SENSITIVITY INDEX	
	TRANSVERSE HOLE	SCRATCHED[*]
Ma	0.386	0.145
Mh	0.675	0.175
FS-la	0.213	0.104
FS-lh	0.417	0.255

[*]Based upon a theoretical stress concentration factor of 2.0

TABLE III

REPEATED FLEXURE FATIGUE STRENGTHS OF 0.064 INCH (a) Ma AND
(b) Mh SHEETS WITH STRESS CONCENTRATIONS DUE TO TRANSVERSE
HOLE AND SCRATCHES, AND THEIR CORRESPONDING STRESS CONCEN-
TRATION FACTOR.   STRESSES ARE IN POUNDS PER SQUARE INCH.

(a)

CYCLES TO FAILURE

CONDITION OF SPECIMEN

CYCLES TO FAILURE	PLAIN Stress	TRANSVERSE HOLE Stress	Factor	SCRATCHED Stress	Factor
5×10^3	15,800	12,750	1.24	13,800	1.15
10^4	13,500	10,750	1.26	12,000	1.13
5×10^4	10,600	8,000	1.33	9,600	1.12
10^5	9,900	7,250	1.35	9,000	1.11
5×10^5	8,900	6,000	1.48	8,250	1.08
10^6	8,600	5,700	1.51	8,000	1.08
5×10^6	8,250	5,100	1.62	7,800	1.05
10^7	8,200	5,000	1.64	7,750	1.05
		Average	1.43	Average	1.09
		Maximum	1.64	Maximum	1.15

(b)

CYCLES TO FAILURE

CONDITION OF SPECIMEN

CYCLES TO FAILURE	PLAIN Stress	TRANSVERSE HOLE Stress	Factor	SCRATCHED Stress	Factor
5×10^3	22,500	18,600	1.21	20,200	1.11
10^4	20,600	16,500	1.25	18,200	1.13
5×10^4	16,400	12,100	1.36	14,000	1.16
10^5	14,900	10,350	1.45	12,600	1.18
5×10^5	12,400	7,000	1.79	10,600	1.16
10^6	11,750	6,100	1.93	10,200	1.15
5×10^6	10,800	5,100	2.12	9,600	1.14
10^7	10,600	5,000	2.12	9,500	1.13
		Average	1.65	Average	1.14
		Maximum	2.12	Maximum	1.18

TABLE IV

REPEATED FLEXURE FATIGUE STRENGTHS OF 0.064 INCH (a) FS-1a AND (b) FS-1h SHEETS WITH STRESS CONCENTRATIONS DUE TO TRANSVERSE HOLE AND SCRATCHES AND THEIR CORRESPONDING STRESS CONCENTRATION FACTORS. STRESSES ARE IN POUNDS PER SQUARE INCH.

(a)

CYCLES TO FAILURE	CONDITION OF SPECIMEN				
	PLAIN Stress	TRANSVERSE HOLE Stress	Factor	SCRATCHED Stress	Factor
5×10^3	22,900	19,000	1.21	20,900	1.09
10^4	20,800	16,750	1.25	18,800	1.10
5×10^4	17,200	13,000	1.34	15,400	1.10
10^5	15,900	12,100	1.31	14,500	1.09
5×10^5	14,300	10,700	1.34	13,400	1.07
10^6	13,800	10,300	1.34	13,200	1.05
5×10^6	13,000	9,600	1.35	12,800	1.02
10^7	12,800	9,500	1.34	12,750	1.01
		Average	1.31	Average	1.07
		Maximum	1.35	Maximum	1.10

(b)

CYCLES TO FAILURE	CONDITION OF SPECIMEN				
	PLAIN Stress	TRANSVERSE HOLE Stress	Factor	SCRATCHED Stress	Factor
5×10^3	29,600	21,750	1.36	24,500	1.21
10^4	26,300	19,100	1.38	22,000	1.19
5×10^4	20,000	13,700	1.46	16,800	1.19
10^5	19,300	13,000	1.49	15,300	1.26
5×10^5	18,400	11,800	1.56	14,600	1.25
10^6	18,000	11,400	1.58	14,400	1.25
5×10^6	17,100	10,250	1.67	14,000	1.22
10^7	16,600	9,750	1.69	13,800	1.21
		Average	1.52	Average	1.22
		Maximum	1.69	Maximum	1.26

APPENDIX II, Figures
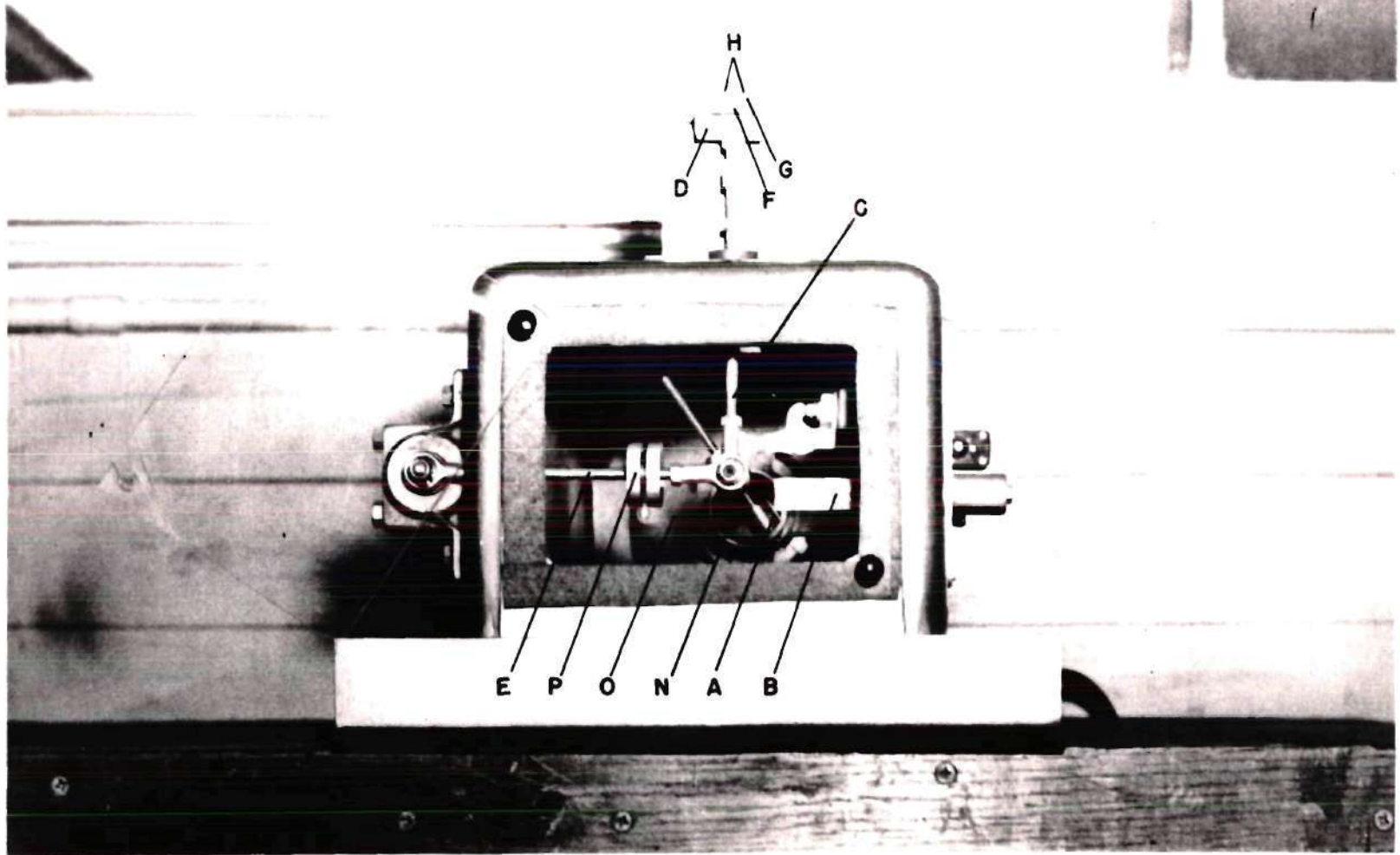
FIGURE 1. SONNTAG FLEXURE FATIGUE MACHINE, MODEL SF-2
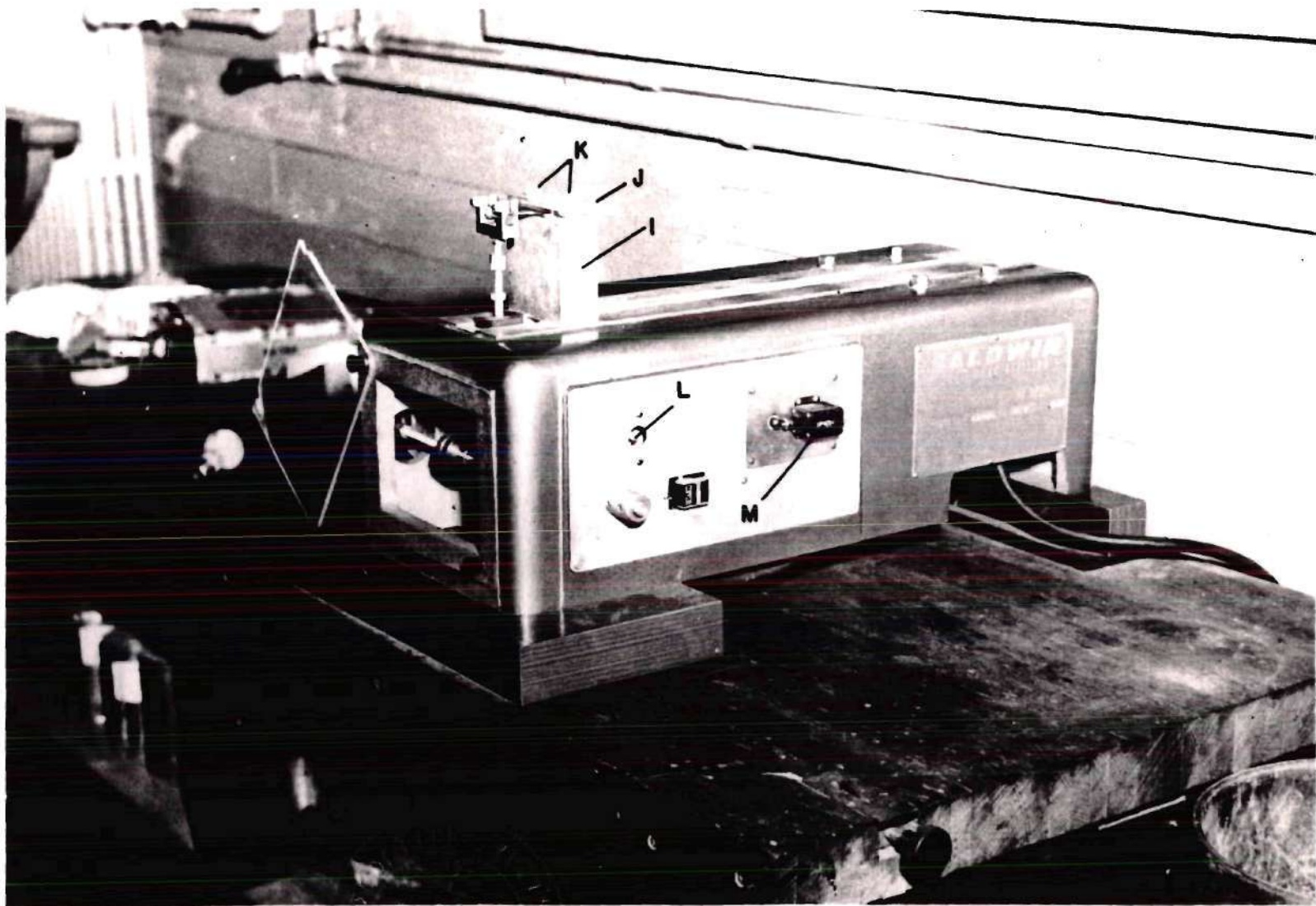
FIGURE 2. SONNTAG FLEXURE FATIGUE MACHINE, MODEL SF-2
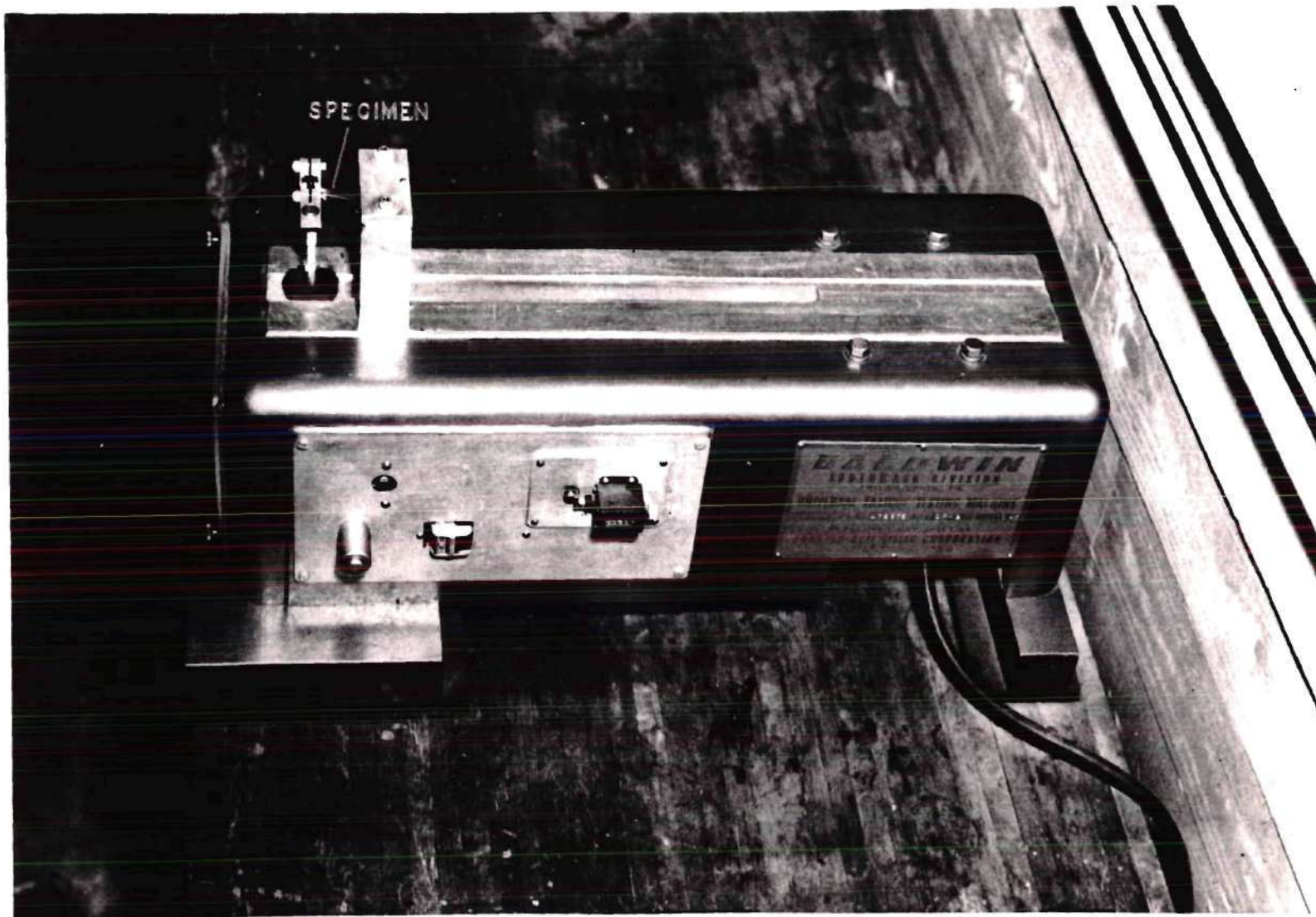
SPECIMEN

FIGURE 5. VIEW SHOWING SPECIMEN LOADED IN SONNTAG FLEXURE FATIGUE MACHINE

50

FIGURE 4. SPECIMEN AND MOUNTING DETAILS

STATIONARY MOUNT

$1\frac{5}{8}$

FREE SPAN

LOAD YOKE
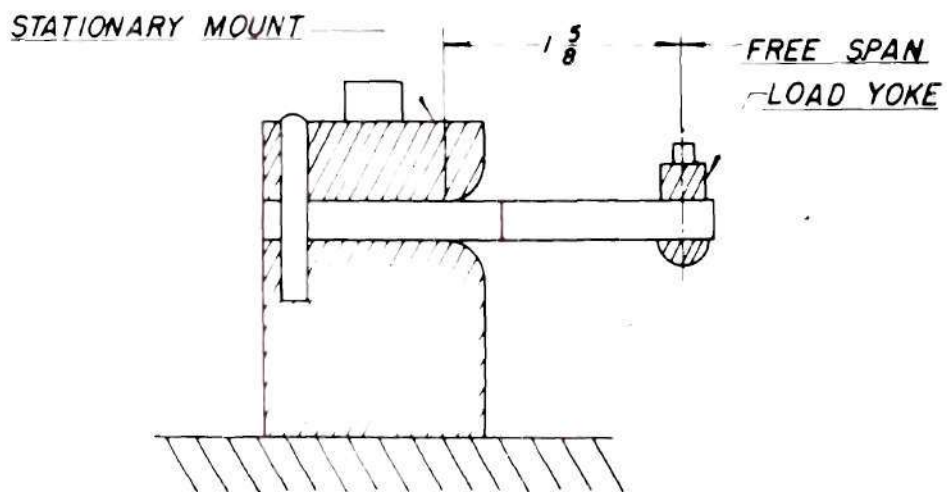
CROSS SECTIONAL VIEW OF
SPECIMEN MOUNTING

DRILL NO. 11 (0.191) 1 HOLE

$\frac{3}{16}$ DRILL 2 HOLES

$\frac{13}{32}$ $\frac{3}{8}R$

$\frac{13}{16}$

$\frac{15}{32}$

2    $\frac{15}{16}$

$\frac{1}{4}$ $\frac{15}{32}$

$\frac{13}{32}$ $\frac{3}{8}R$ $\frac{1}{8}$

$\frac{5}{16}$

$\frac{3}{16}$ $1\frac{7}{16}$ $1\frac{1}{4}$

$3\frac{1}{16}$
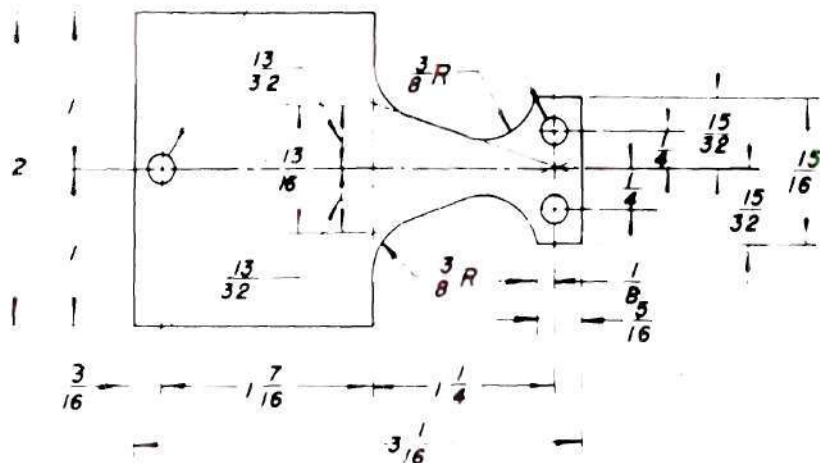
SPECIMEN DETAILS
ALL DIMENSIONS IN INCHES

TEMPLATE

CLAMP
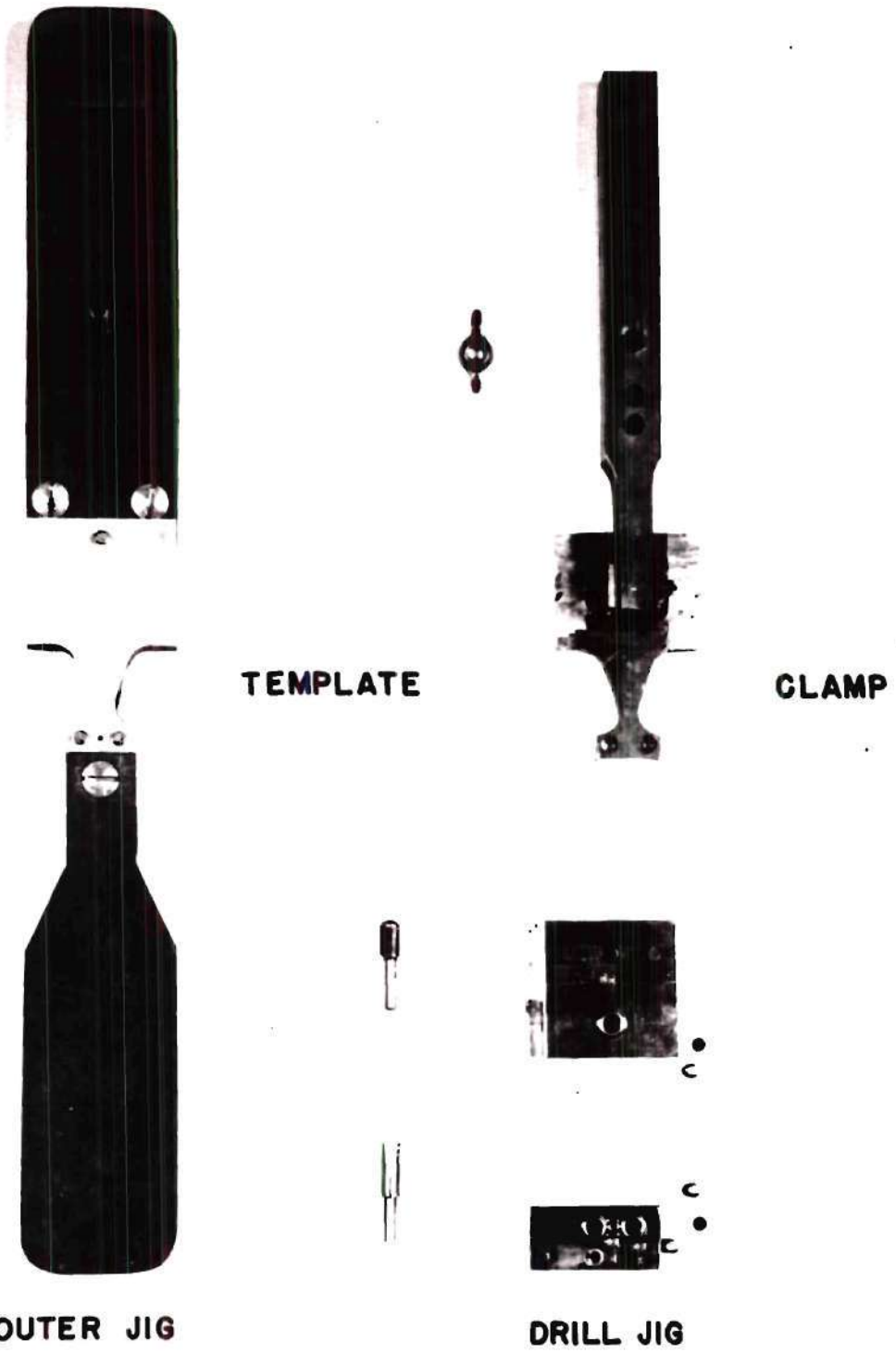
ROUTER JIG

DRILL JIG

FIGURE 5. PHOTOGRAPH OF DRILL JIG AND ROUTER JIG

PLAIN

TRANSVERSE HOLE

SCRATCHED

RIVETED
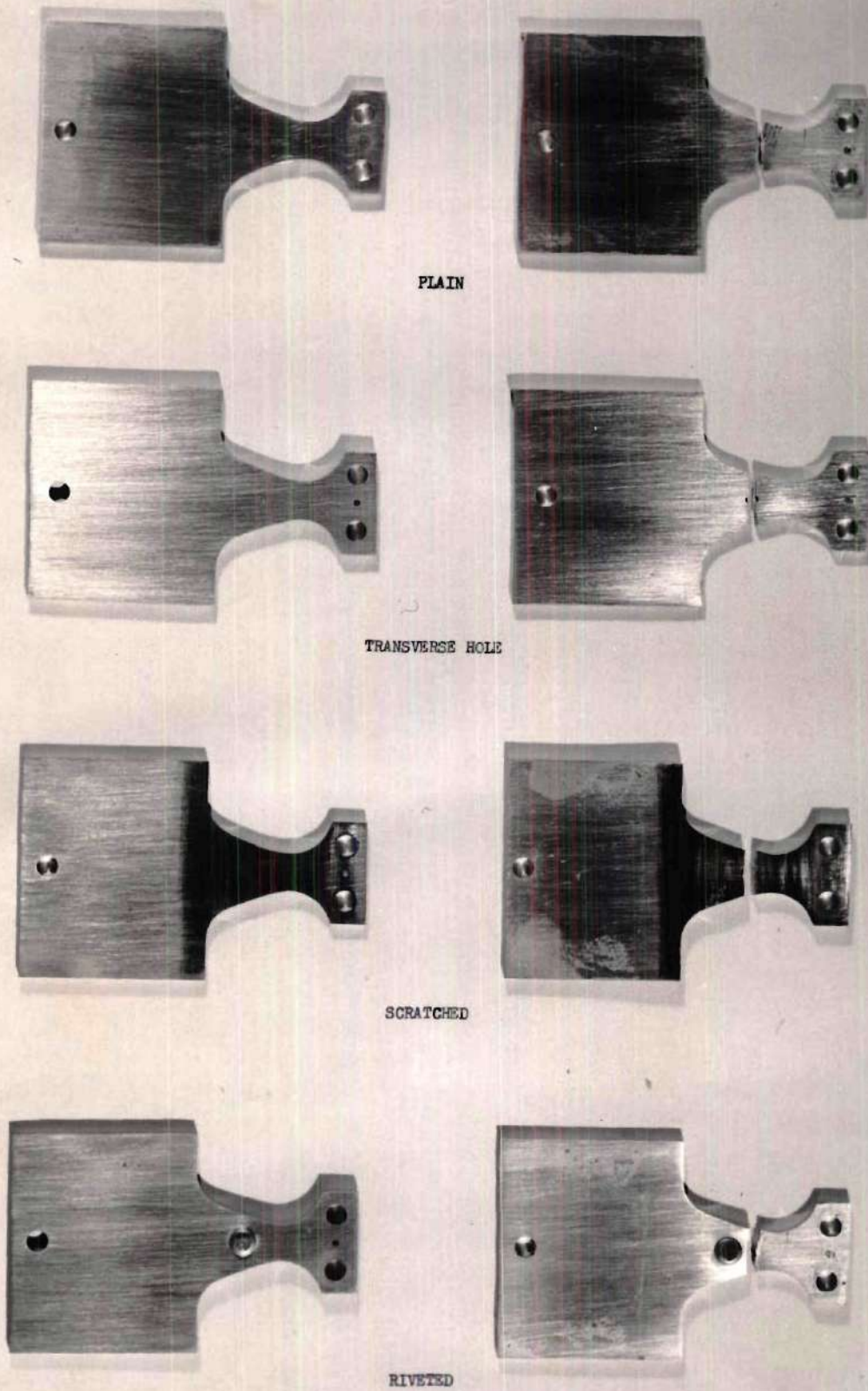
FIGURE 6. PHOTOGRAPH OF SPECIMENS BEFORE AND AFTER FAILURE DUE TO FATIGUE TESTING DESCRIBING LOCATION AND TYPE OF STRESS CONCENTRATION
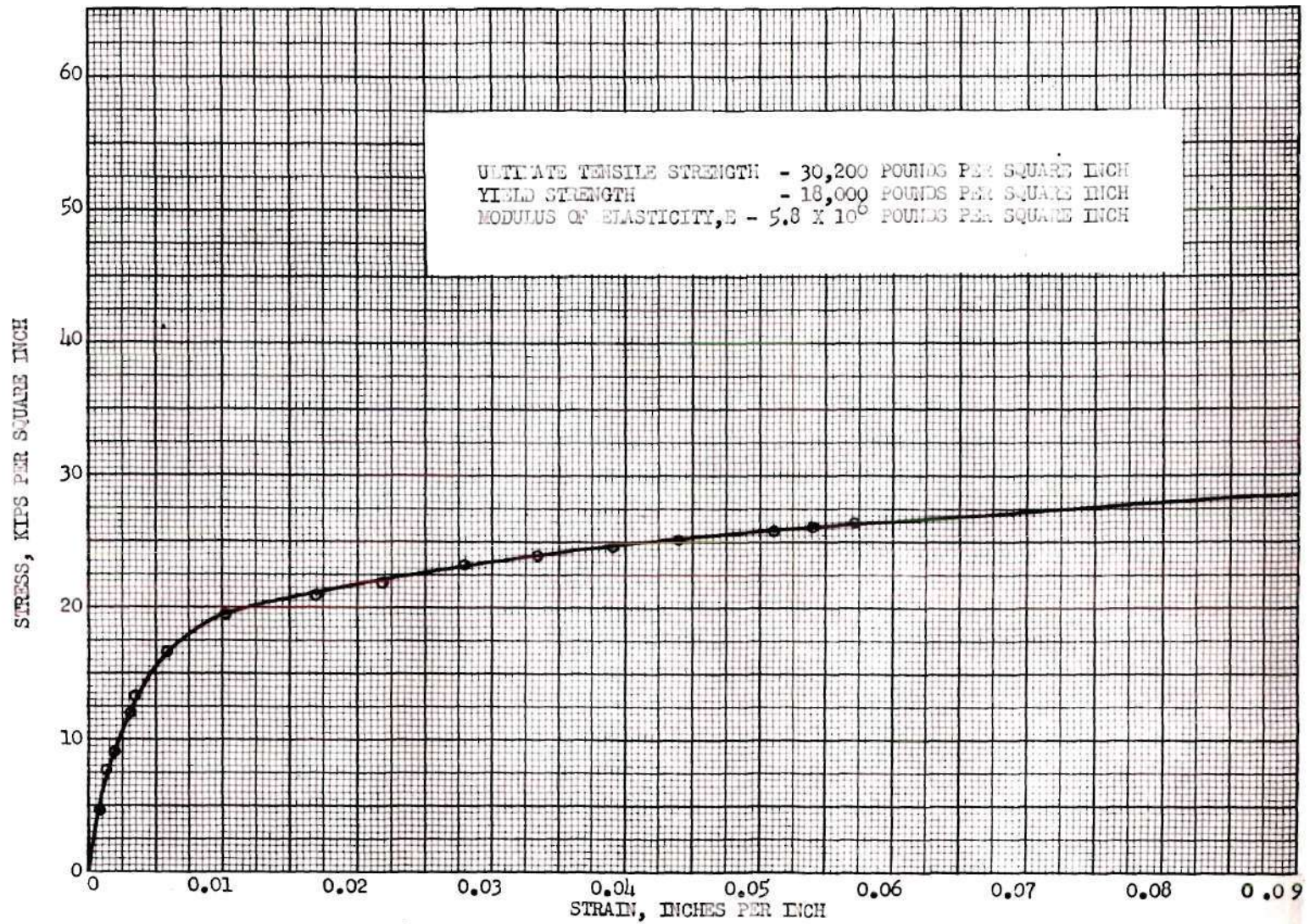
FIGURE 7. TENSILE STRESS-STRAIN CURVE FOR 0.064 INCH Ha MAGNESIUM ALLOY SHEET

The figure contains the following annotations:

ULTIMATE TENSILE STRENGTH — 30,200 POUNDS PER SQUARE INCH
YIELD STRENGTH — 18,000 POUNDS PER SQUARE INCH
MODULUS OF ELASTICITY, E — 5.8 X 10^6 POUNDS PER SQUARE INCH

Axis labels:
STRESS, KIPS PER SQUARE INCH
STRAIN, INCHES PER INCH

ULTIMATE TENSILE STRENGTH — 32,600 POUNDS PER SQUARE INCH
YIELD STRENGTH — 28,200 POUNDS PER SQUARE INCH
MODULUS OF ELASTICITY, E — 6.4×10^6 POUNDS PER SQUARE INCH

STRESS, KIPS PER SQUARE INCH

STRAIN, INCHES PER INCH

FIGURE 8.   TENSILE STRESS-STRAIN CURVE FOR 0.064 INCH Mh MAGNESIUM ALLOY SHEET
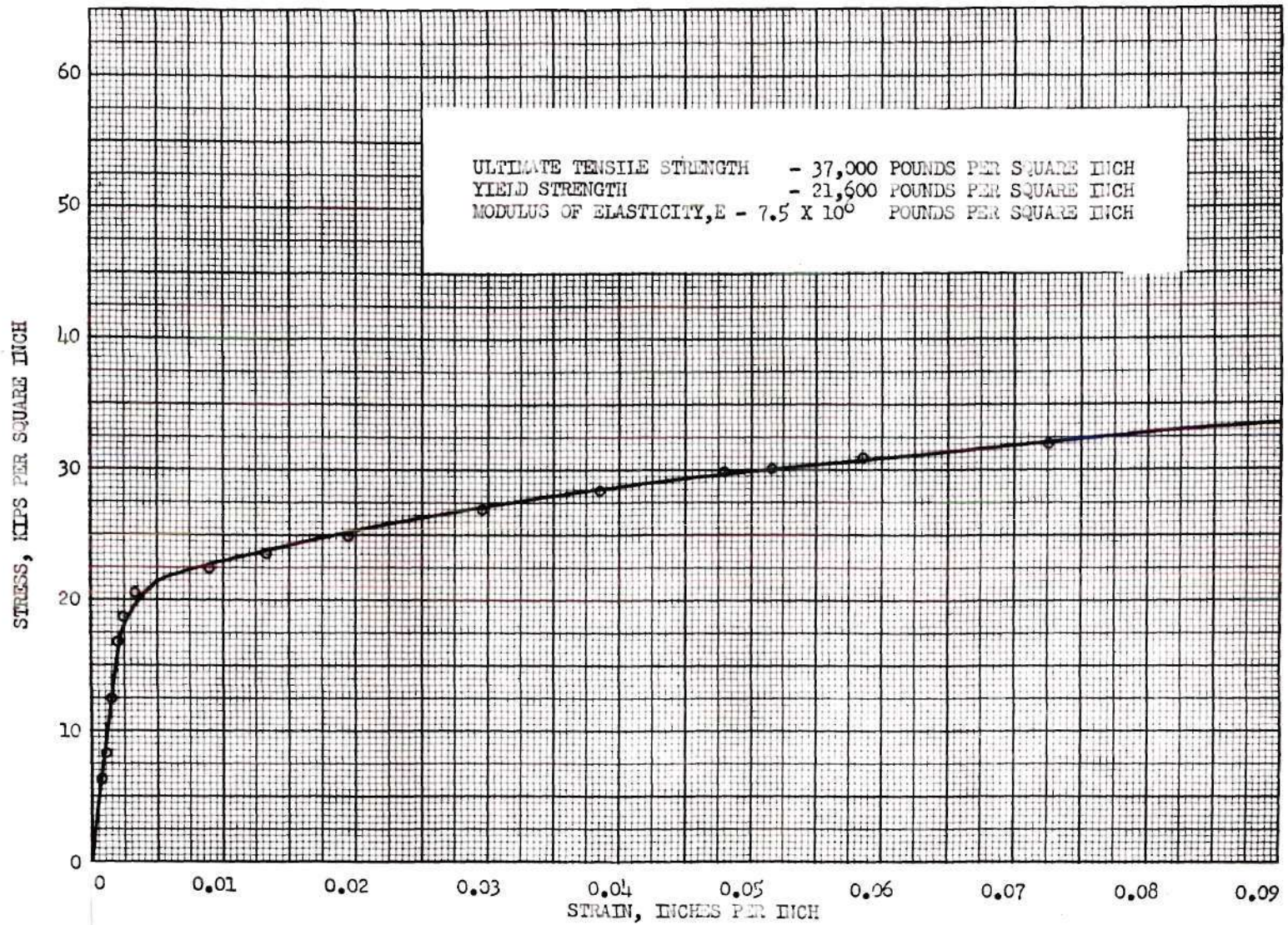
FIGURE 9. TENSILE STRESS-STRAIN CURVE FOR 0.064 INCH FS-1a MAGNESIUM ALLOY SHEET
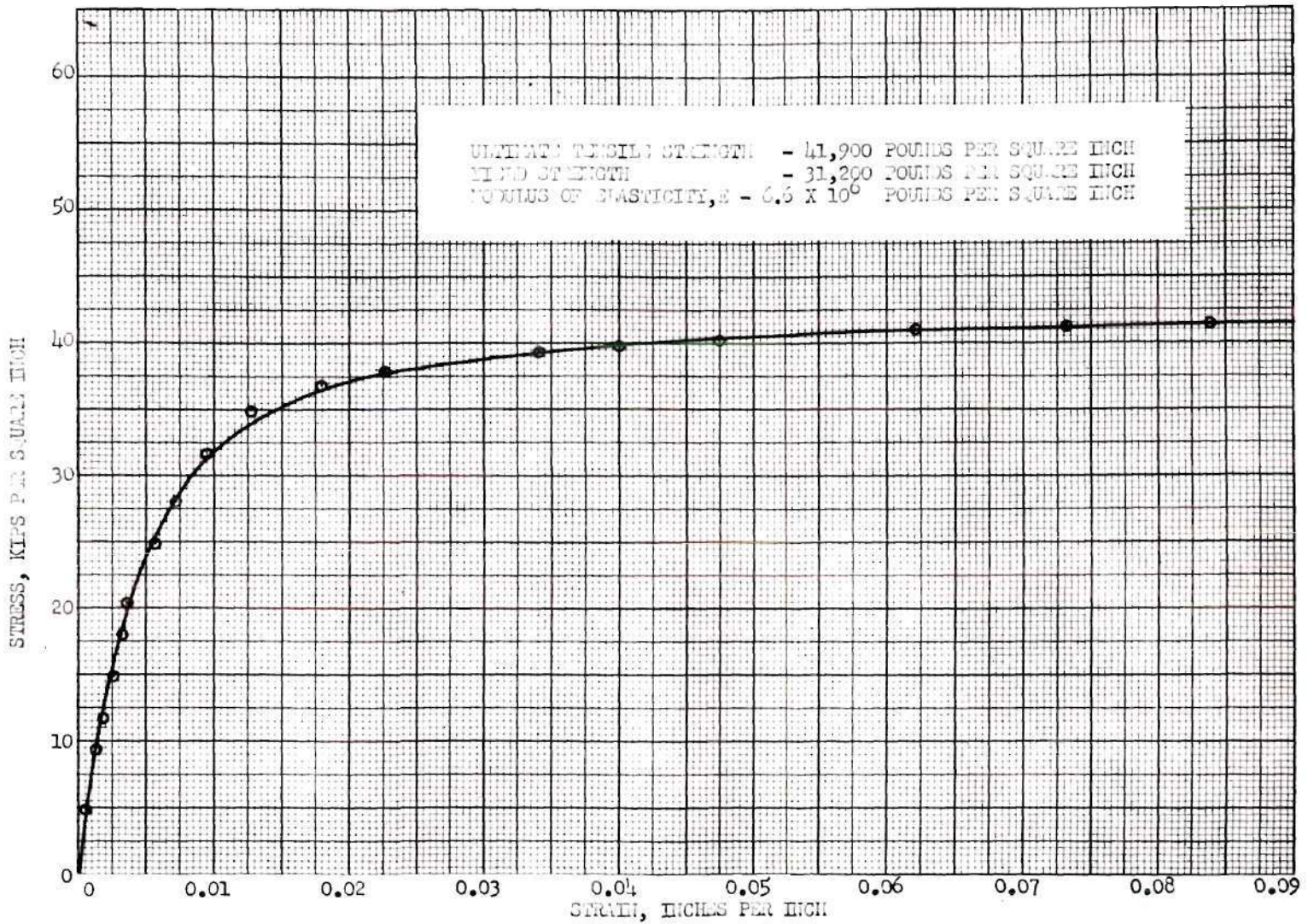
FIGURE 10. TENSILE STRESS-STRAIN CURVE FOR 0.064 INCH FS-1h MAGNESIUM ALLOY SHEET
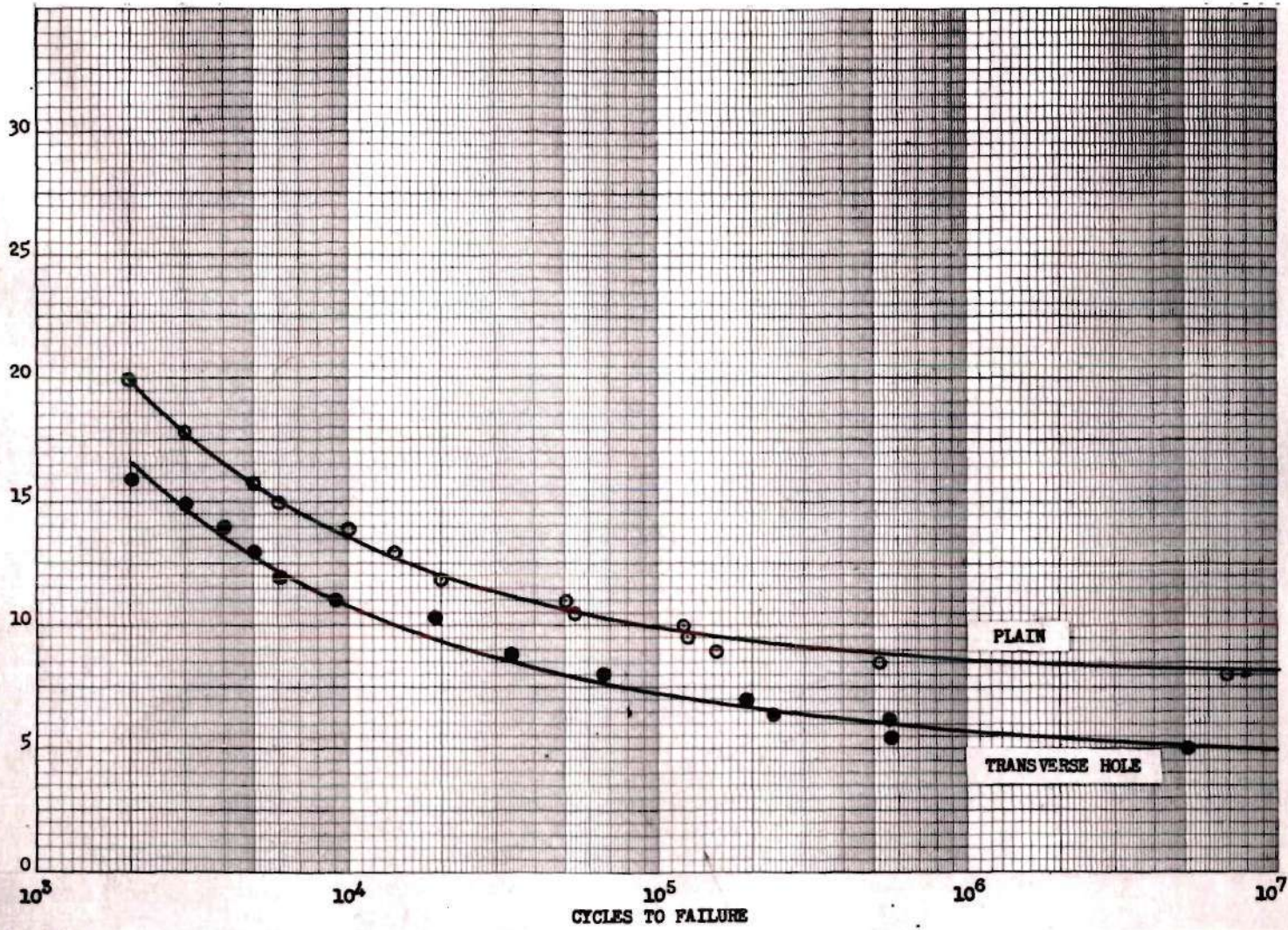
FIGURE 11. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH Ma SHEET, PLAIN SPECIMENS AND SPECIMENS WITH TRANSVERSE HOLE
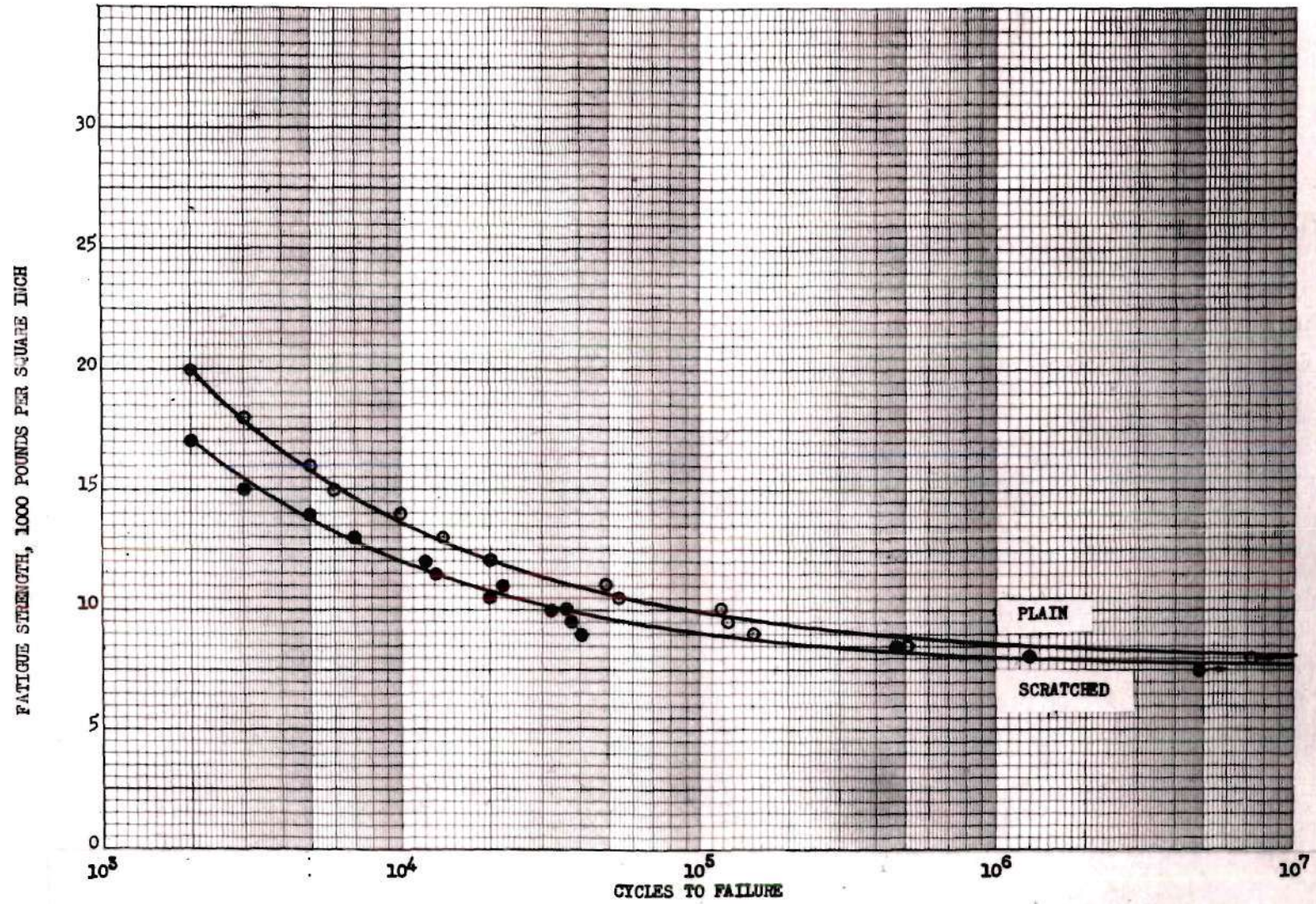
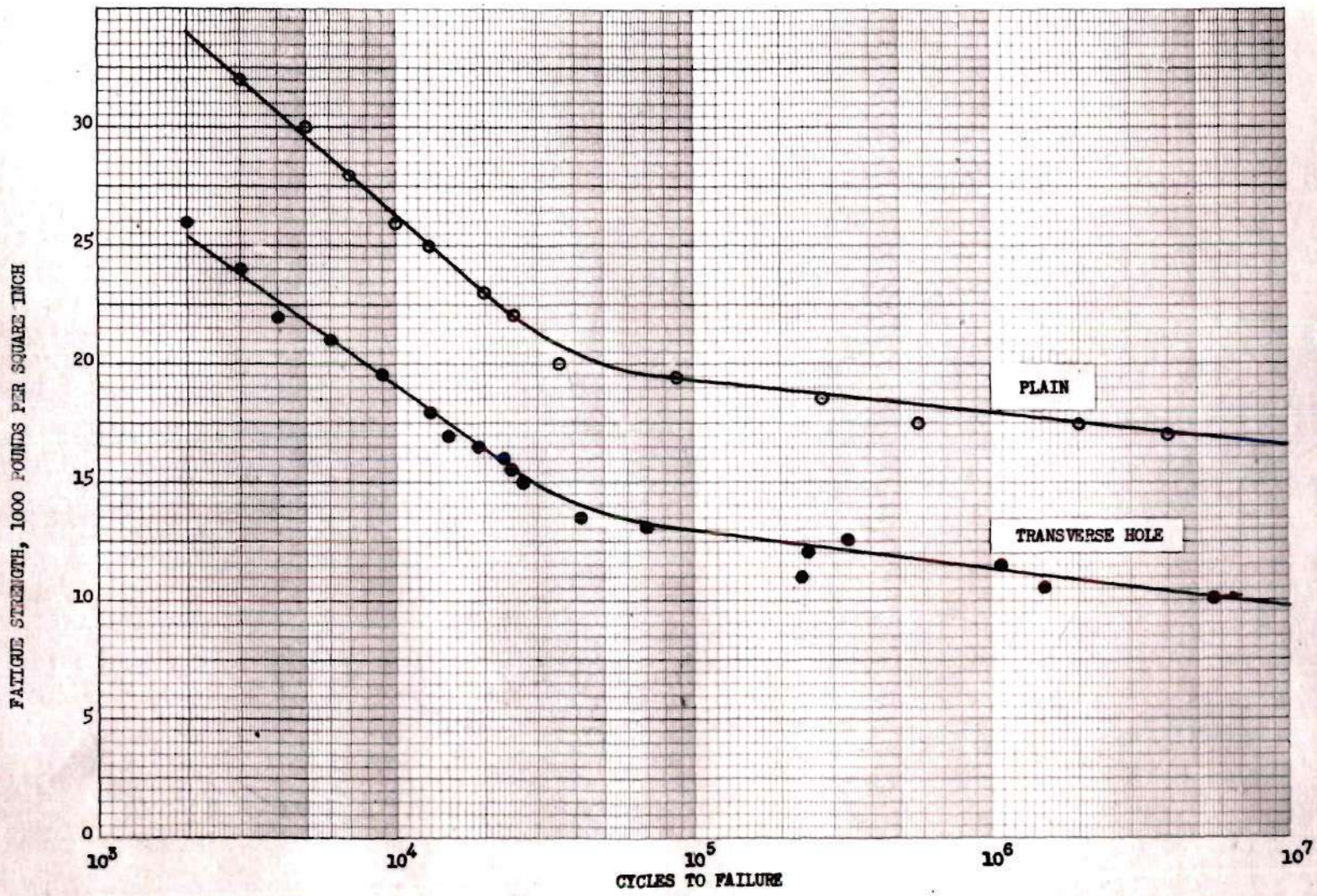FIGURE 12. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH Mg SHEET, PLAIN AND SCRATCHED SPECIMENS

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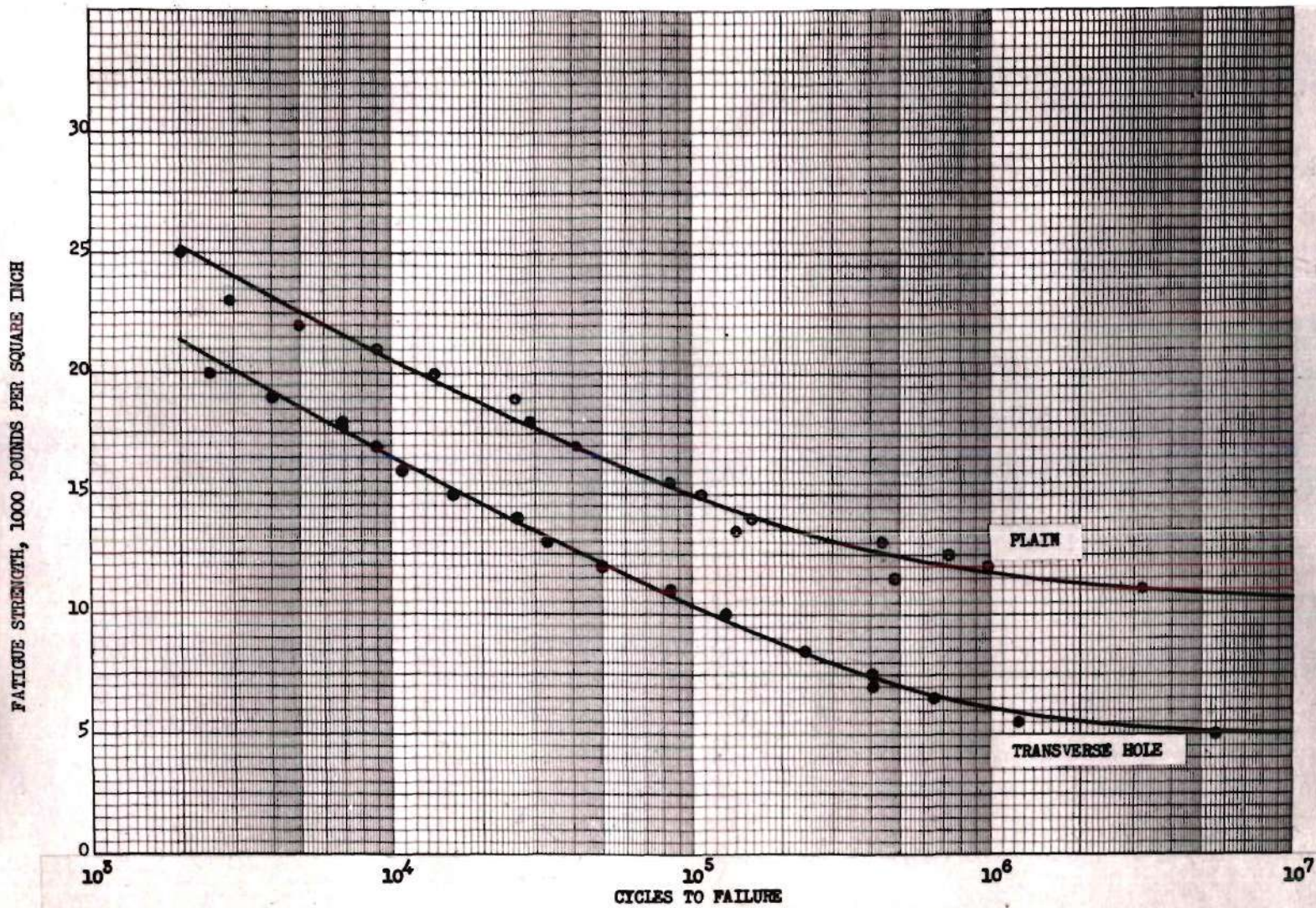
FIGURE 15. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH Mh SHEET, PLAIN SPECIMENS AND SPECIMENS WITH TRANSVERSE HOLE
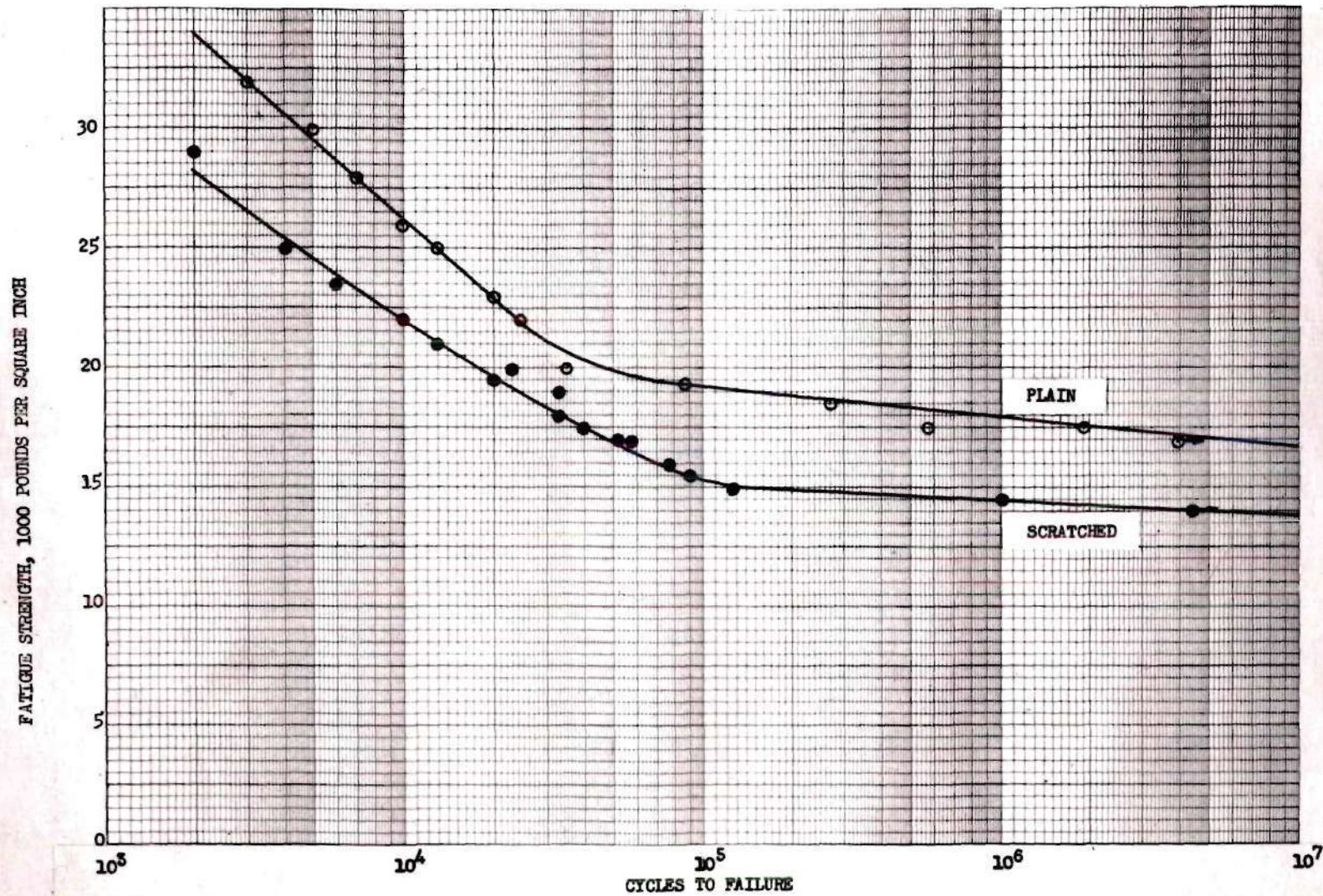
60
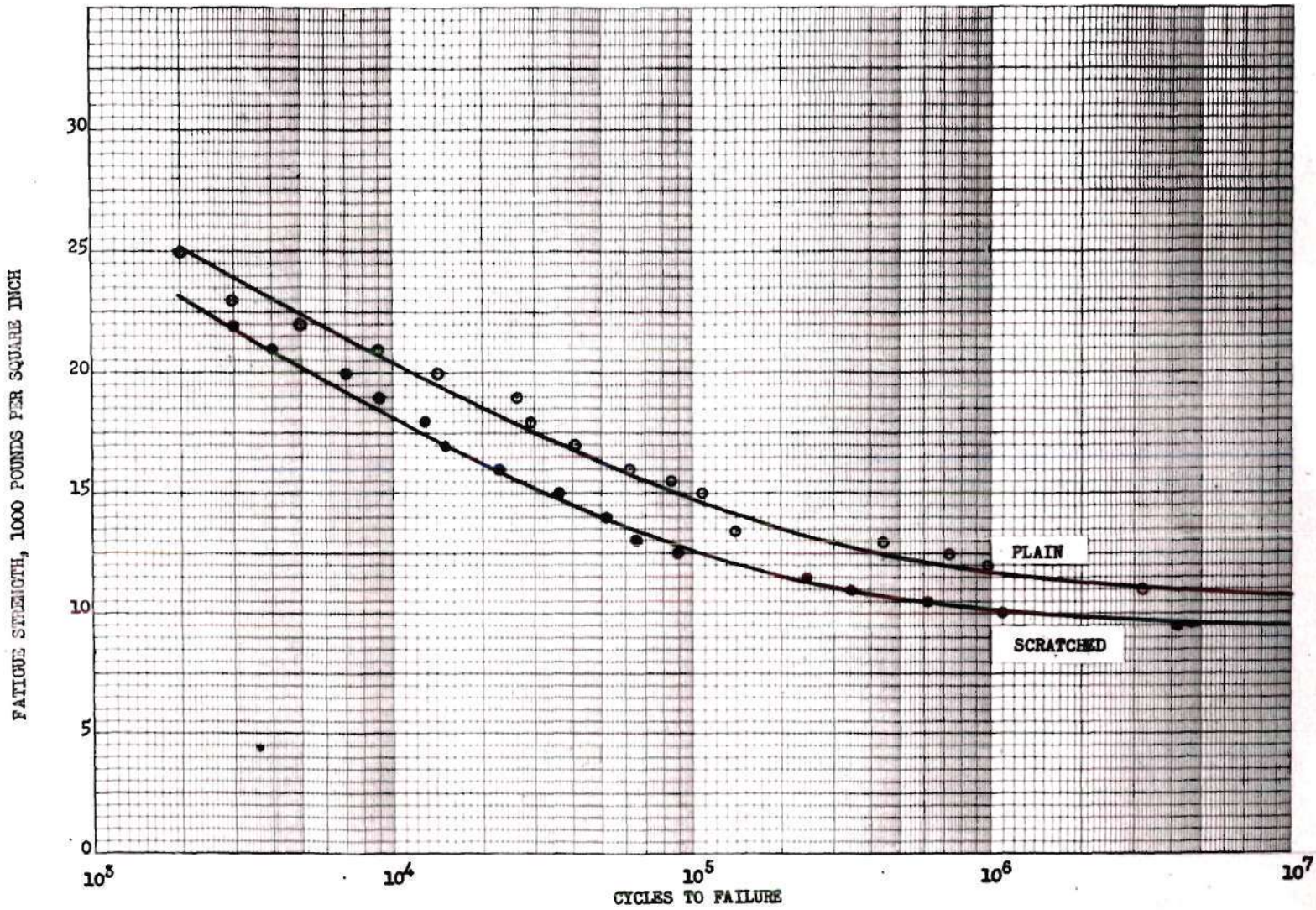
FIGURE 14. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH Mh SHEET, PLAIN AND SCRATCHED SPECIMENS
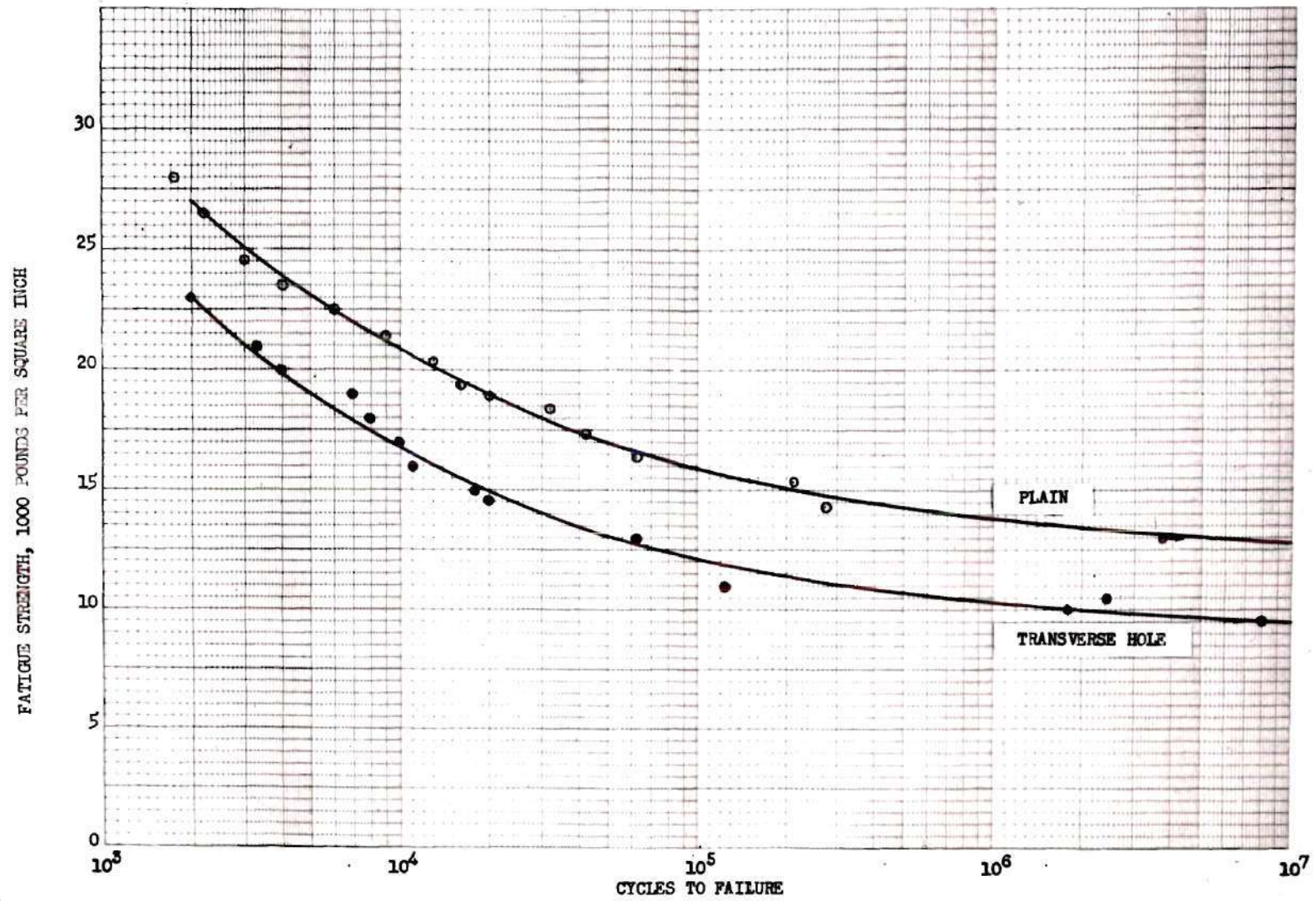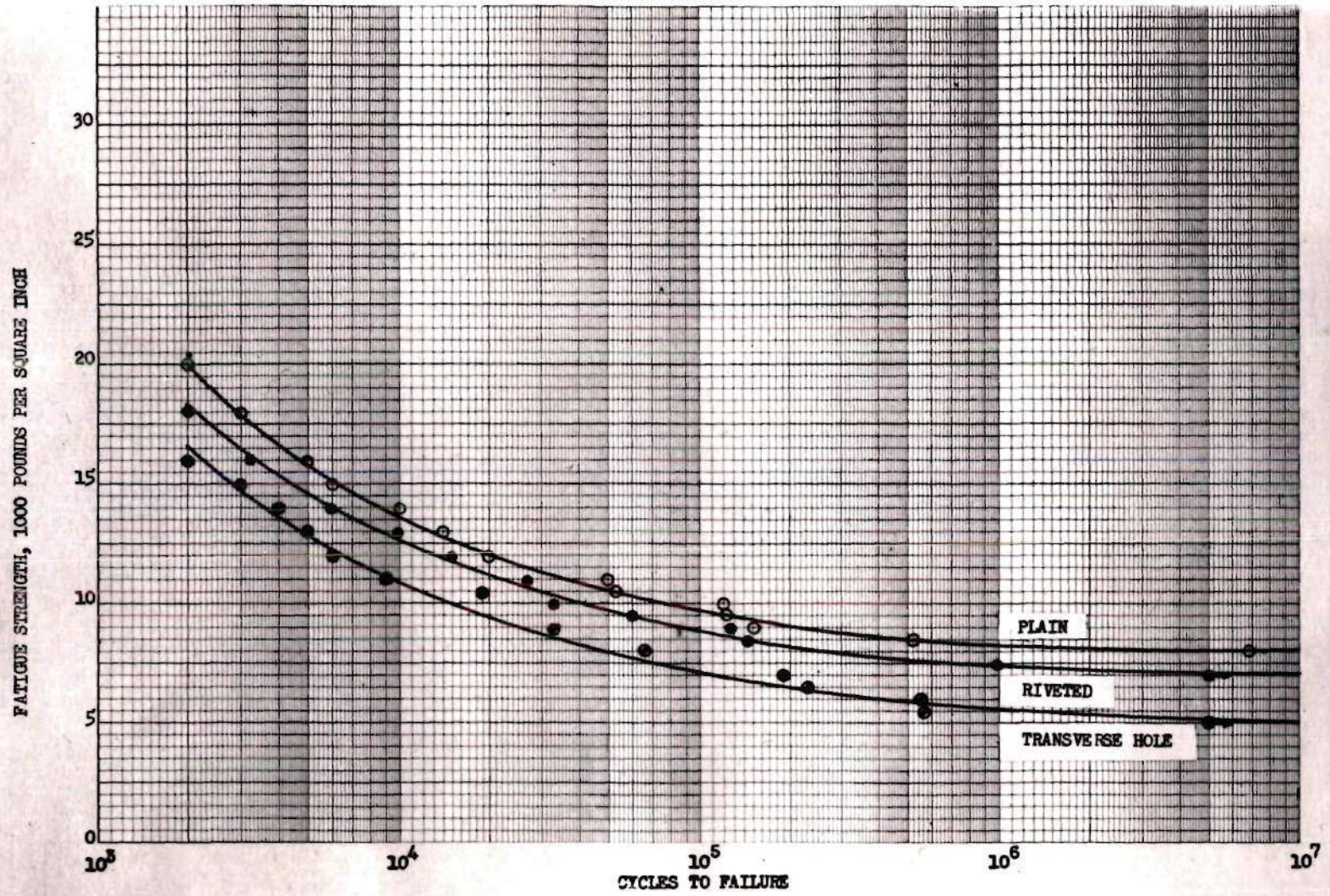
FIGURE 15. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH FS-1a SHEET, PLAIN SPECIMENS AND SPECIMENS WITH TRANSVERSE HOLE
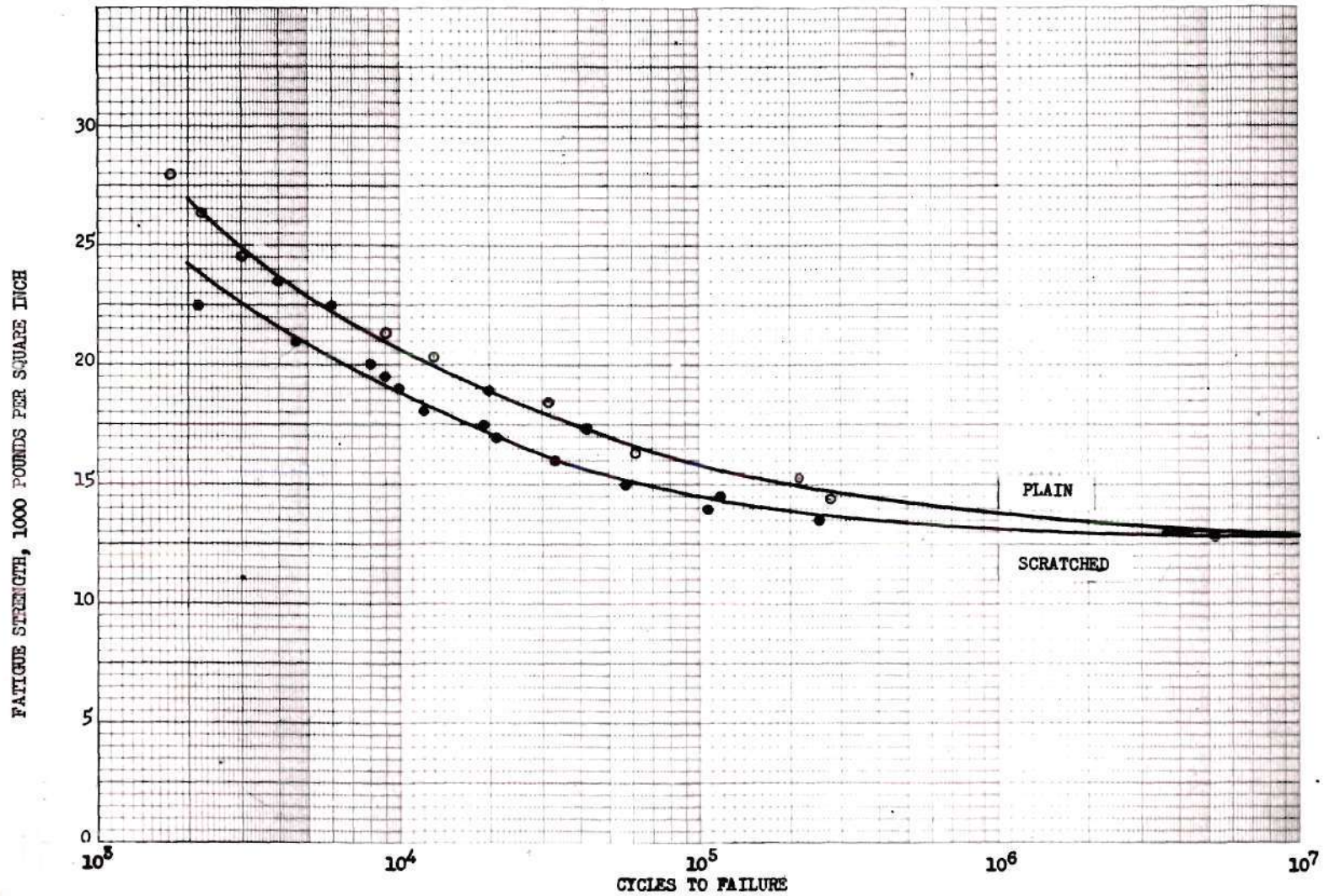
FIGURE 16. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH FS-1a SHEET, PLAIN AND SCRATCHED SPECIMENS

FIGURE 17. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH FS-1h SHEET, PLAIN SPECIMENS AND SPECIMENS WITH TRANSVERSE HOLE

FIGURE 18. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH FS-1h SHEET, PLAIN AND SCRATCHED SPECIMENS

FIGURE 19. REPEATED FLEXURE FATIGUE TEST RESULTS FOR 0.064 INCH Ma SHEET SHOWING THE EFFECT OF RIVET IN TRANSVERSE HOLE
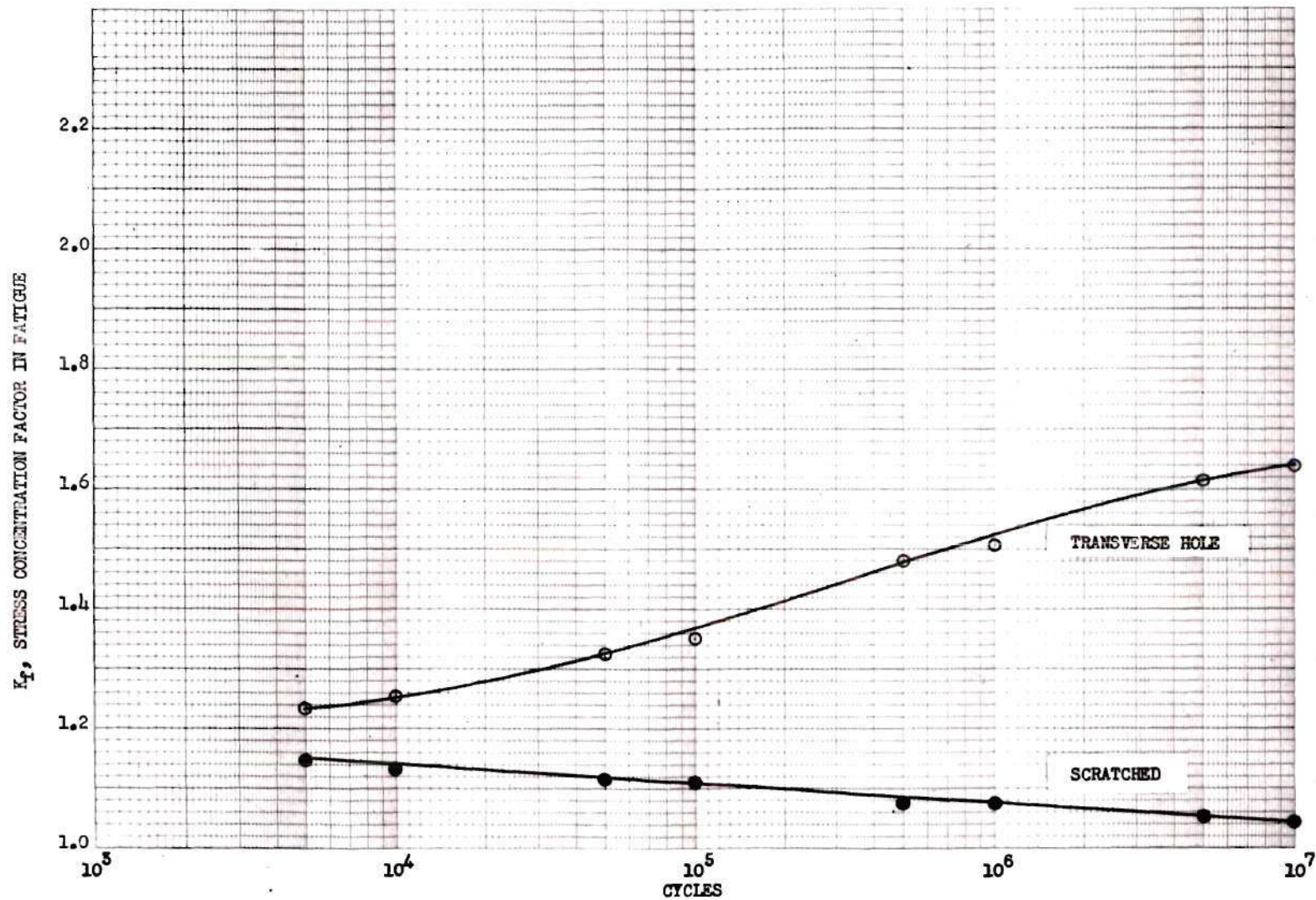
FIGURE 20.   VARIATION OF STRESS CONCENTRATION FACTOR WITH FATIGUE LIFE OF 0.064 INCH Ma SHEET
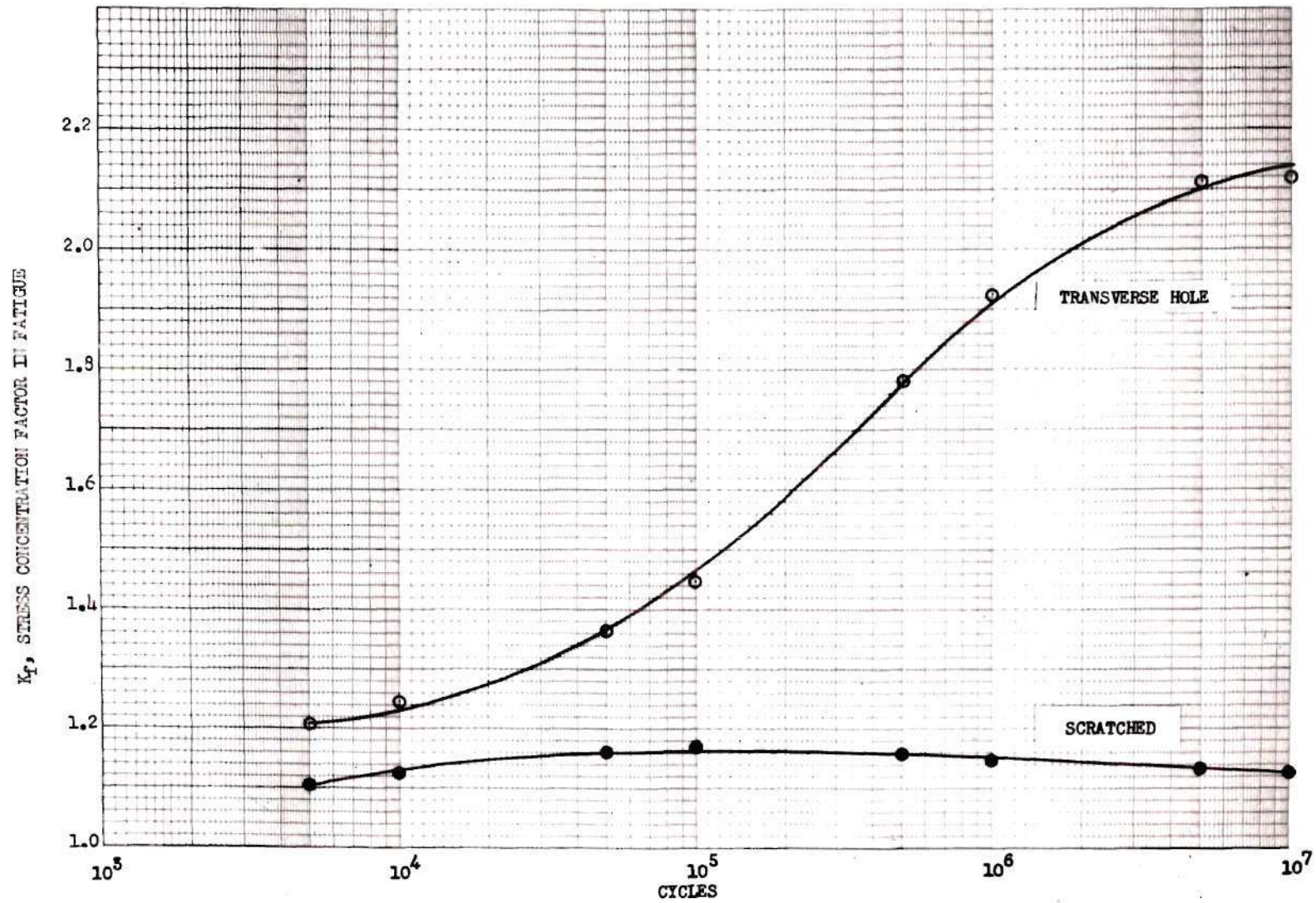
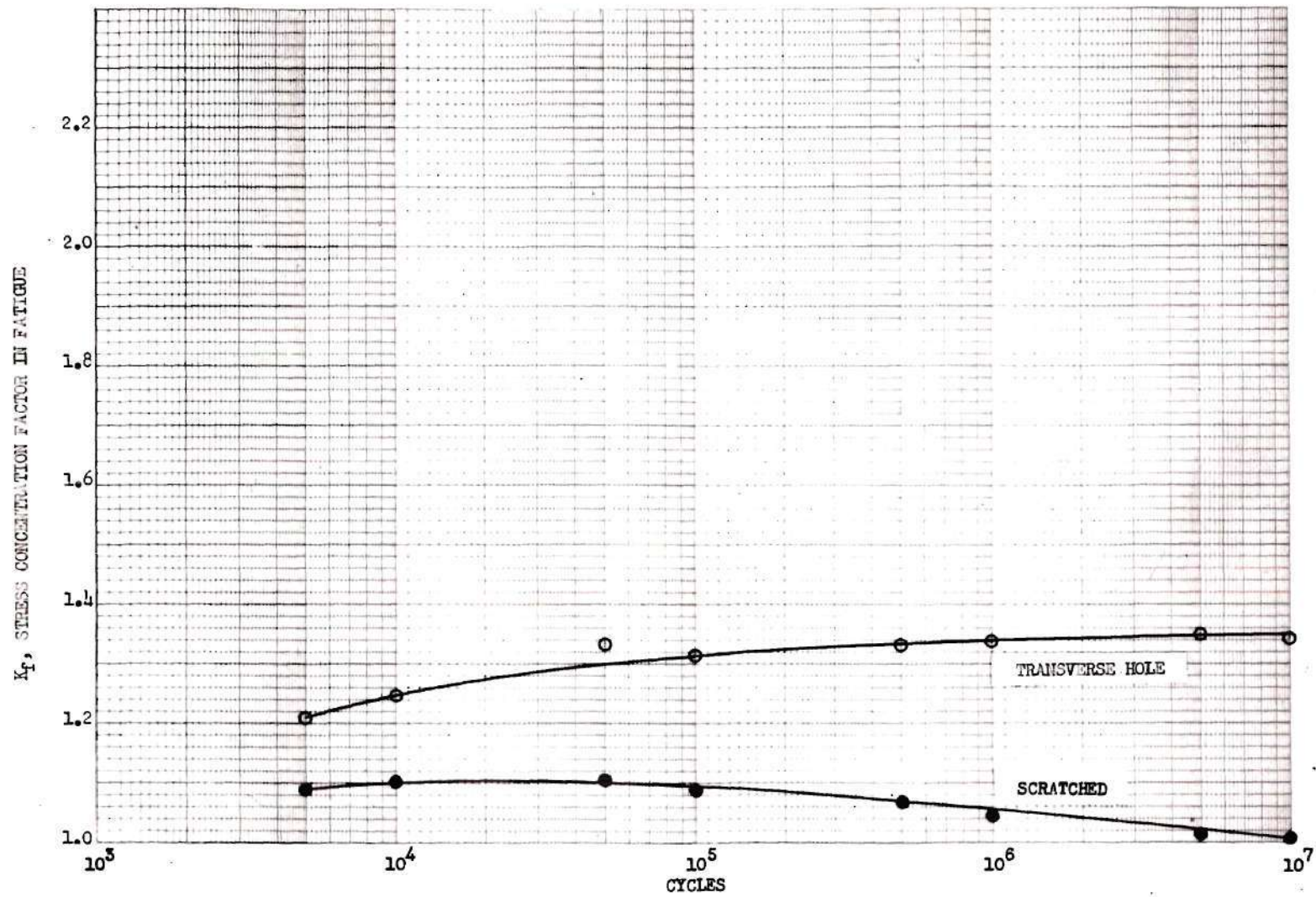FIGURE 21. VARIATION OF STRESS CONCENTRATION FACTOR WITH FATIGUE LIFE OF 0.064 INCH Mh SHEET

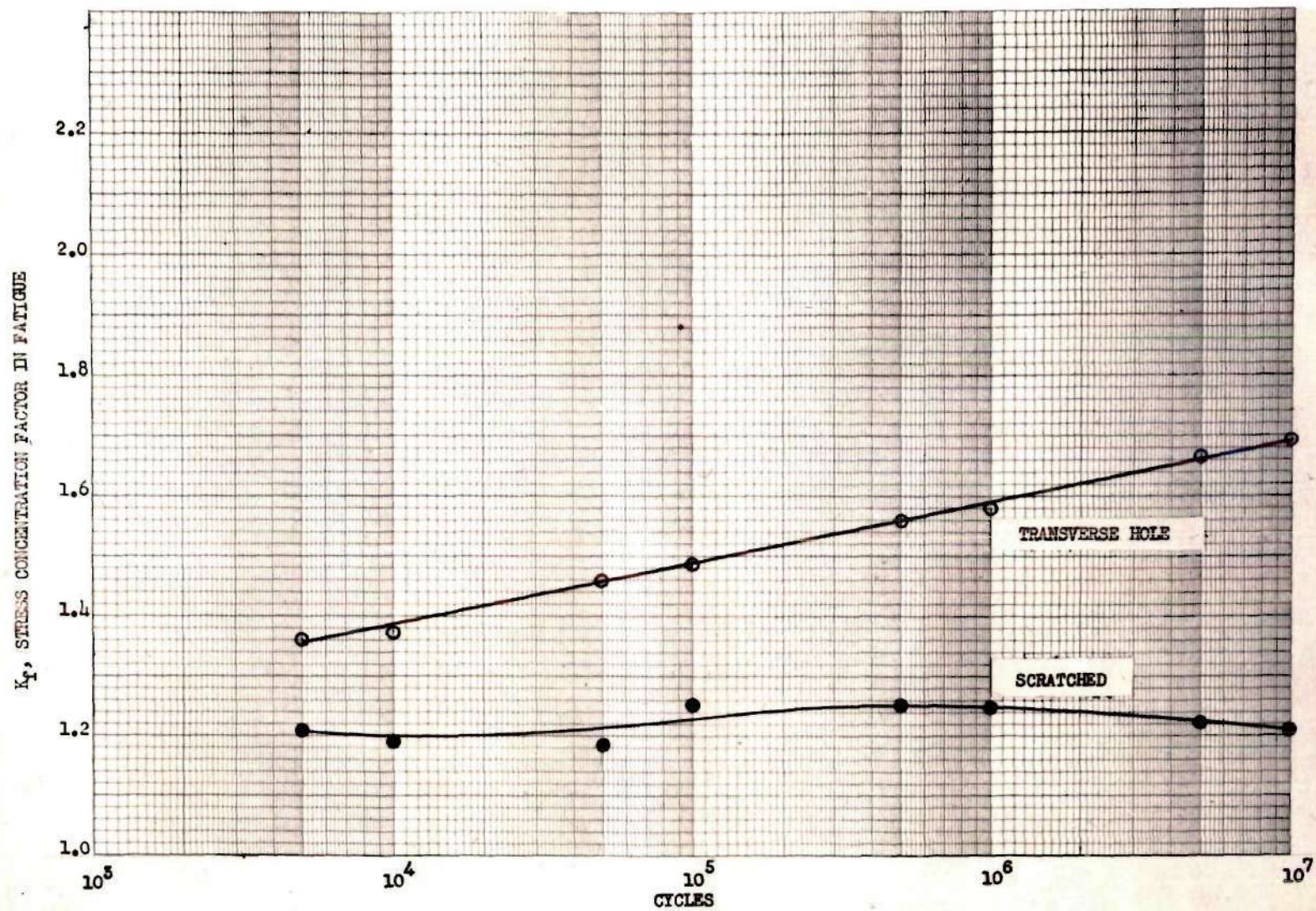FIGURE 22. VARIATION OF STRESS CONCENTRATION FACTOR WITH FATIGUE LIFE OF 0.064 INCH FS-1a SHEET

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FIGURE 25. VARIATION OF STRESS CONCENTRATION FACTOR WITH FATIGUE LIFE OF 0.064 INCH FS-1h SHEET