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TECHNICAL NOTE

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AXIAL FATIGUE TESTS AT ZERO MEAN STRESS OF 24S-T ALUMINUM-ALLOY SHEET WITH AND WITHOUT A CIRCULAR HOLE

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National Bureau of Standards

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SUMMARY

Axial fatigue tests were made on 189 coupon specimens of 0.032-inch 24S-T aluminum-alloy sheet and a few supplementary specimens of 0.064-inch sheet. The mean load was zero. The specimens were restrained against lateral buckling by lubricated solid guides described in a previous report on this project. About two-thirds of the 0.032-inch specimens were plain coupons nominally free from stress raisers. The remainder contained a 0.1285-inch drilled hole at the center where the reduced section was 0.5 inch wide. S-N diagrams were obtained for cycles to failure between about 1000 and 10^7 cycles for the plain specimens and 17 and 10^7 cycles for the drilled specimens. The fatigue stress concentration factor increased from about 1.08 for a stress amplitude causing failure at 0.25 cycles (static) to a maximum of 1.83 at 15,000 cycles and then decreased gradually. The graph for the drilled specimens showed less scatter than that for the plain specimens.

INTRODUCTION

In spite of the importance of aluminum-alloy sheet in aircraft, there is a noticeable lack of information in the literature regarding its fatigue properties. For instance, the early part of the S-N curve between 0.25 and 10^5 cycles has received little attention; the effect on the fatigue strength of stress raisers such as holes has not been thoroughly investigated; more information is needed on the fatigue properties at different mean stresses and on the cumulative effect of different stress amplitudes.

Most of the tests which have been made on sheet metals have been of the flexural type; that is, a bending moment was applied to the specimen and the maximum fiber stress was calculated by the simple beam theory. In service, sheet metals are nearly always loaded under direct stresses; hence it is necessary to evaluate the flexural-test results in terms of direct or axial stresses. Investigation on steel and aluminum-alloy bar stock has shown (reference 1) that usually lower fatigue stresses for failure at a given number of cycles are obtained from direct axial loading than from flexural fatigue tests on rotating beams and on fixed beams. The use of flexural fatigue data for describing the fatigue strength under direct stress is particularly questionable in the case of alclad aluminum alloys because of the yielding of the aluminum coating under relatively small extreme fiber stresses.

Axial fatigue tests of sheet metal are complicated by certain practical difficulties, such as gripping the specimen, axial loading with negligible bending, and prevention of buckling when the stress cycle includes compressive loads.

The NACA in 1942 requested the National Bureau of Standards to conduct a research project on axial fatigue tests to overcome these difficulties and to obtain more adequate fatigue data on high-strength aluminum-alloy sheet for aircraft.

A previous report (reference 2) describes the technique that was developed for this project.

The present report gives the S-N curve up to about 10^7 cycles for 24S-T aluminum-alloy sheet with and without a circular hole. The purpose in testing the drilled specimen was to show by an example the effect of a typical stress concentration. No comprehensive investigation of stress concentration has been attempted.

This investigation, conducted at the National Bureau of Standards, was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

MACHINES

Most of the results were obtained in machine a (figs. 1 to 3), which was constructed at the National Bureau of Standards. This machine consists of a heat-treated tubular lever A (fig. 1), an adjustable crank B, a connecting rod adjustable by means of the turnbuckle C, wire strain gages D mounted on the tube, a Baldwin-Southwark Wheatstone bridge control box E with micrometer balancing adjustment F for the wire gages, decade resistance boxes G in series with the wire gages, relays H, a revolution counter I, horizontal and vertical flexure plates J and K (fig. 2) at the fulcrum of the lever, jaw L (fig. 3) at the end of the lever; stationary jaw M, and limit switch N which operates the relays H to stop the machine when the specimen breaks. A specimen O supported by lateral guides P described in reference 2 is held in the jaws. The alternating component of the load is set statically by adjusting the crank B to produce an unbalance of the Wheatstone bridge corresponding to that load. The steady component or mean load is set by adjusting turnbuckle C. The sensitivity of the Wheatstone bridge was adjusted by setting the decade resistances G so that one division on the barrel of the micrometer screw corresponded to a load change of 2 pounds. The machine was calibrated statically by hanging dead weights on jaw L or by applying a load through a proving ring. A dynamic calibration was also made and was reported in reference 2. It indicated that for the specimens tested in the present investigation the "dynamic overthrow" of the lever amounted to 6.5 percent at 1000 rpm. This amount was added to the static load to obtain the dynamic load.

The machine may be set to any mean load, tension, or compression, such that the minimum and maximum loads lie within the range 1500 pounds compression to 1500 pounds tension. Abrasive paper was placed between each side of the specimen and the grip to prevent slipping. The abrasive side was in contact with the specimen. Carborundum Company waterproof polishing paper No. 400A was used.

Some specimens were tested in machine b (fig. 4) which is an adaptation of one designed by the Aluminum Company of America (reference 3). Oscillating motion is imparted by the eccentric A to the Scotch yoke B, which is connected in series with the specimens C and the elastic loop dynamometers D. The struts E have flexure plates at each end. Rotation of the motor-driven shaft F causes approximately sinusoidal alternations of the loads which differ in phase by 180° in the two specimens. The alternating component of the load is determined by the setting of the eccentric A; the steady component or mean load by the position of the nuts G. The load is measured by holding the pointed feet of the dial micrometer H in two gage holes in the top of the loop and reading the dial at the minimum and maximum loads as the flywheel is slowly rotated by hand. The dial gage was checked repeatedly on the standard bar I which contains fixed gage holes spaced about the same as those in the loop at zero load. The loops are occasionally removed from the machine and calibrated in a dead-weight calibrating machine. The counter J indicates the number of cycles.

The capacity of the machine is ±1500 pounds; that is, the minimum and maximum loads must lie within this range. The dynamic calibration in reference 2 showed that the dynamic overthrow of machine b was less than the experimental error of the load measurements; consequently the dynamic load was assumed to be equal to the static. The specimens were clamped under setscrews and abrasive paper was used in the grips as in machine a. The design of the machine provided for another pair of specimens at the back end of the shaft, but the parts have not yet been constructed.

The lateral guides described in reference 2 and shown in figures 3 and 4, or similar guides, were used on all specimens. It is shown in reference 2 that these guides effectively restrain the specimen from buckling without introducing a measurable amount of friction. It was also found that the crosswise distribution of stress was satisfactorily uniform; the difference in the amplitude of the dynamic strain measured on each edge of the specimen by means of 2-inch Tuckerman strain gages (fig. 4, reference 2) was usually less than 1 percent.

SPECIMENS

Types I and II (fig. 5) are the same except for the hole. The hole diameter 0.1285 inch was selected because it is the diameter widely used for 1/8-inch rivets. The type-I and type-II specimens that were tested in machine a were slightly wider at the ends and shorter, but had the same reduced section. The reduced section is tapered toward the middle to avoid failure at the shoulder, where the result for type I might be lowered by stress concentration. A few type-III specimens were tested to determine whether a 2:1 increase in the cross-sectional dimensions affected the results; likewise a few type-IV were included to determine the effect of increasing the size of the specimen in relation to the size of the hole.

The reduced-section specimens were machined in a drill press by means of the apparatus shown in figure 6. A stack of specimens is clamped on the template B, the edges of which are curved in accordance with the long radius of the reduced section. The template is separated from the button C, which is centered under the cutter D, by a spacing strip E. A cut is made by feeding vertically after which the clamp is released, the stack is advanced lengthwise to a new position, reclamped, and another cut made. This is repeated until the stop F is in contact with the button. Successively thinner spacers E are inserted until, for the finishing cut, none is used. The humps which remain on the edges are removed by polishing with emery cloth and finishing with fine steel wool. When the specimens are separated the slight burr that remains on the edge is removed with fine polishing paper. Care was taken not to round the edge. Each specimen in the stack is separated from adjacent specimens by sheets of thin paper. This apparatus readily permits changes in the dimensions of the specimens for experimental purposes but is somewhat slow and requires hand work. When the form of the specimen is standardized it is planned to prepare them by milling with a formed cutter.

MATERIAL

Specimens were taken in the longitudinal direction from two sheets, A and B, of 0.032-inch aluminum-alloy 24S-T, and one sheet, C, of 0.064-inch. Sheet A was obtained in 1937 under Navy Department Specification No. 47A10; its dimensions were 16 by 168 inches. Sheets B and C were obtained in 1943 under Navy Department Specification No. 47A10e; their dimensions were 48 by 144 inches. Sheet A had a few slight scratches resulting from handling; sheets B and C were carefully protected and virtually free from scratches. Sheets A and B presented the surface condition shown enlarged in figure 7 to a degree varying with the location. The surface contained numerous small fissures transverse to the specimen. The fissures were observed on both sides of sheet A, but were more prevalent on one side; they were observed on only one side of sheet B. The general surface finish of sheet B resembled one produced by a grinding process.

The static tensile and compressive properties of sheets A and B were determined; the results are given in the table and typical stress-strain curves in figure 8.

TESTS

Type-I and type-II specimens were tested in machine <u>a</u>, except specimens which were tested at high stresses in machine <u>b</u> and the static specimens. All type-III and type-IV specimens were tested in machine <u>b</u>. The static specimens were tested in a tensile testing machine.

The flywheel of machine <u>b</u> was spun by hand for the high-stress specimens which required only a few hundred load cycles; only one was tested at a time. Stresses in excess of about 60,000 psi were accompanied by sufficient plastic flow of the specimen to cause binding of the guides; hence no attempt was made to go higher. At the higher stresses it was necessary to readjust the machine several times during the first few cycles, after which the load remained relatively stable until failure.

The highest fatigue stress for the type-II specimens caused failure after 17 cycles. Probably the specimen could have been loaded to still higher stress, but the initial adjustment of the load would have used up a considerable portion of the fatigue life.

RESULTS

S-N curves are given in figure 9. The stress was computed by dividing the maximum load by the product of the thickness and the net width at midlength; the diameter of the hole was subtracted from the gross width of the drilled specimens to obtain the net width. Most of the type-I specimens fractured near the middle; the results were discarded if the fracture occurred at the toe of the fillet. All the drilled specimens fractured at the hole.

The scatter of the type-I specimens is greater for sheet A than for sheet B; this may be due to the fact that more from sheet A were tested. The scatter of the type-I specimens was definitely associated with the surface fissures. An examination of the specimens showed that the fissures were much more prevalent among specimens corresponding to points which fell below the curve representing the average than among specimens the point of which fell above. The damage caused by the fissures varied with the extent to which they occurred. It is believed that they reduced the fatigue strength of the plain specimens by as much as 15 percent in some cases. Their damaging effect was less marked for the drilled specimens and the scatter was relatively less. Probably the stress concentration caused by the hole was more severe than that caused by the fissures and the effect of the fissures was masked by the effect of the hole. The S-N curve of the plain specimens has an upper knee corresponding to a stress exceeding the static yield stress.

The results for type-I specimens are in good agreement with those obtained by Brick and Phillips (reference 4), who used flexural loading and covered the range $N = 2 \times 10^5$ to 10^8 cycles approximately.

To obtain some idea of the consistency of the results a pair of limits for the two curves S and S' (fig. 9) is so placed that approximately one-fourth of the points lie on each side of the band thus formed. Thus the chances are even that a point will fall inside or outside of the band.

The fatigue stress concentration factor k_f (fig. 10) is equal to S/S'. The average value of k_f is about 1.08 for failure under static tension (0.25 cycle), rises to a maximum of 1.83 at 15,000 cycles, then gradually decreases. If, for the purpose of analysis, ΔS and $\Delta S'$ (fig. 9) are treated as the "probable error" of S and S', respectively, band limits may be established in figure 10 to show the resulting probable error in k_f. The equations of the limits were derived from reference 5, section 25. The term "probable error" includes in this case the natural variation in S and S' among different specimens of the same material as well as the experimental error. It was believed that the band limits might show that the hump in the k_f curve (fig. 10) could be attributed to the scatter of the results, but obviously this is not the case.

A few other investigators (references 6 and 7) have determined the fatigue strength of strips containing holes; however, either the material, the manner of loading, or the stress range differed from that in the present investigation. Bürnheim (reference 6) found fatigue stress concentration factors ranging between 1.4 and 1.84 for German duralumin 3116.5 specimens 6 millimeters thick by 40 millimeters wide containing a central 10-millimeter hole and subjected to pulsating tensile loads. The value of the factor was somewhat greater for electron metal 3510.1. Judging by the chemical composition and tensile properties which were given, alloys 3116.5 and 3510.1 apparently correspond to aluminum alloy 17S-T and to magnesium-base alloy 8, Navy Department Specifications Nos. 47A3c and 47M2, respectively. Körber and Hempel (reference 7) tested St37 (designates a steel of tensile strength 37 kg/mm^2 = 52.6 ksi) steel specimens 12 or 13 millimeters thick by 40 to 90 millimeters wide containing one hole 2.5 to 30 millimeters in diameter under completely reversing load. The stress-concentration factor which they show in a graph ranges from 1 to 1.5 as the ratio of the hole diameter to width of specimen varies from 0 to 0.7.

Although a 2:1 increase in the size of the specimen did not appear to affect the results, another investigation in progress at the National Bureau of Standards but as yet uncompleted, has indicated a size effect.

Obviously it will be difficult to correlate different fatigue results obtained on stress-concentration specimens until the effects of material, mean stress, and size are further investigated.

CONCLUSION

Results of axial fatigue tests at zero mean stress are presented for both a plain coupon-type 24S-T sheet specimen and for specimens containing a circular hole. Fatigue strength was affected by surface fissures which were present in the sheet. The results for the plain specimens show fair agreement with flexural results published by Brick and Phillips. Specimens containing a circular-hole stress concentration showed less scatter than did plain specimens. Tests on sheet-metal specimens containing typical stress concentrations promise to be more useful than similar tests on plain specimens after results obtained on different types of stress concentrations are correlated.

National Bureau of Standards,
Washington, D. C., June 1944.

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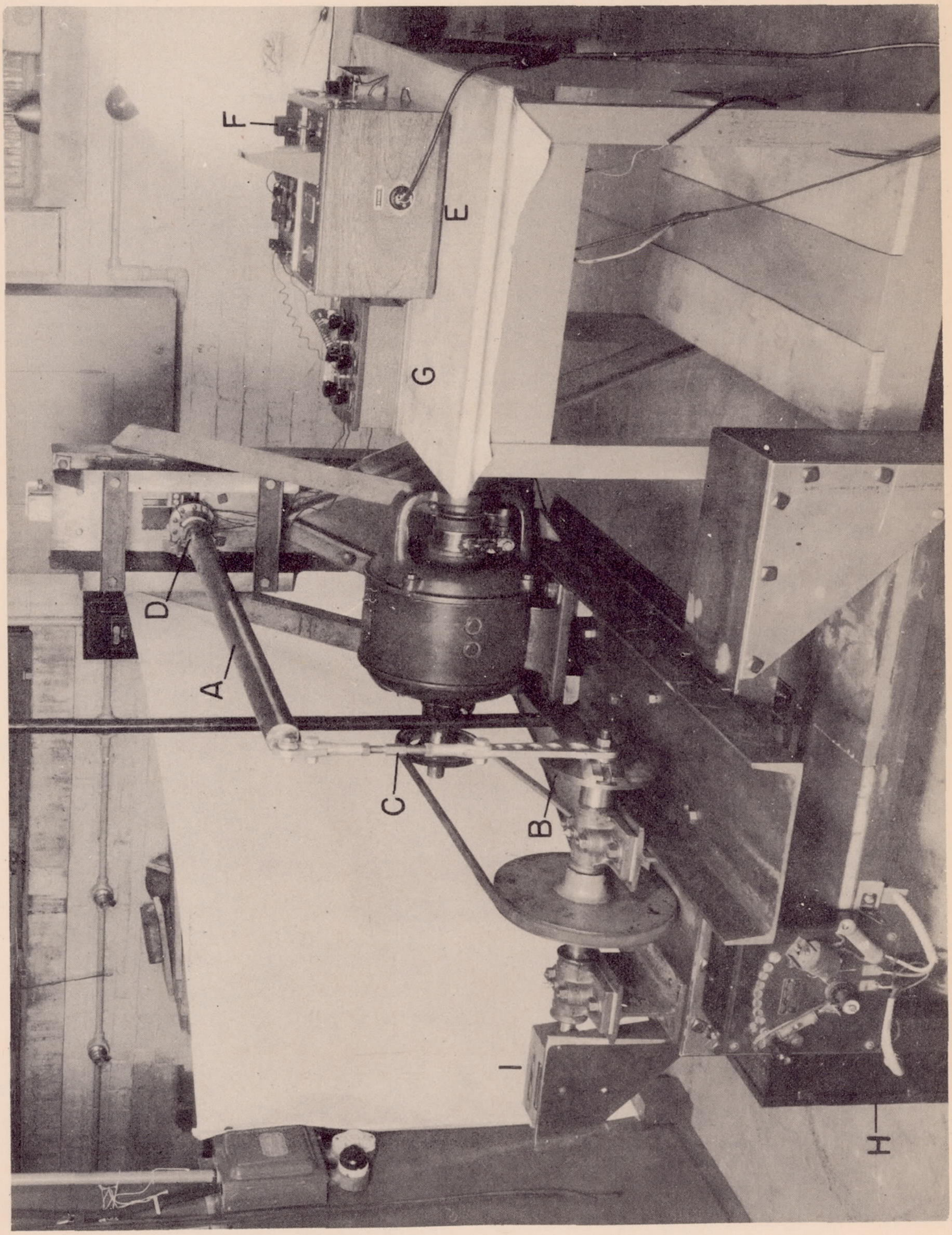

Figure 1.- Machine *a*.

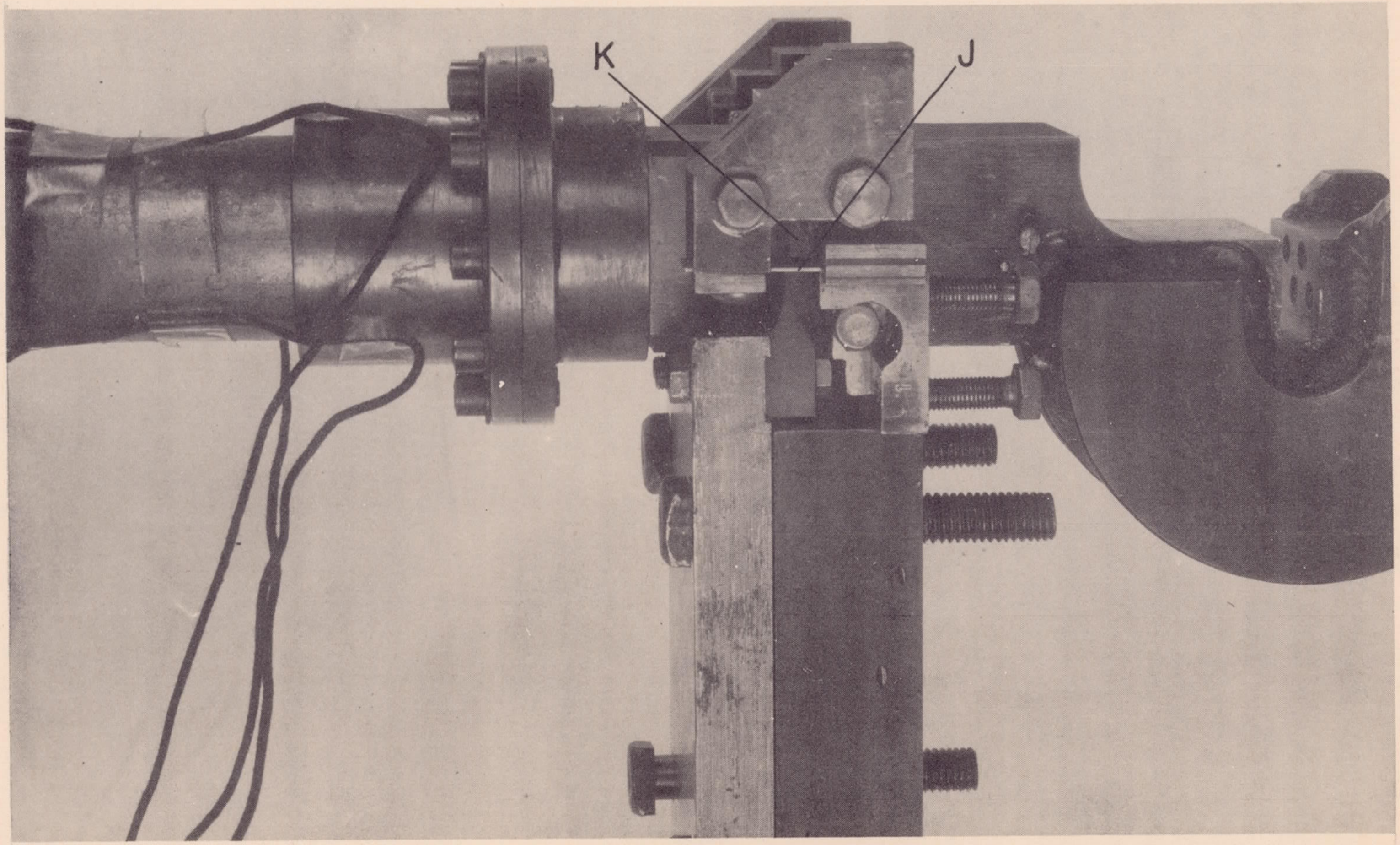

Figure 2.- Lever fulcrum of machine a showing horizontal and vertical flexure plates J and K respectively.

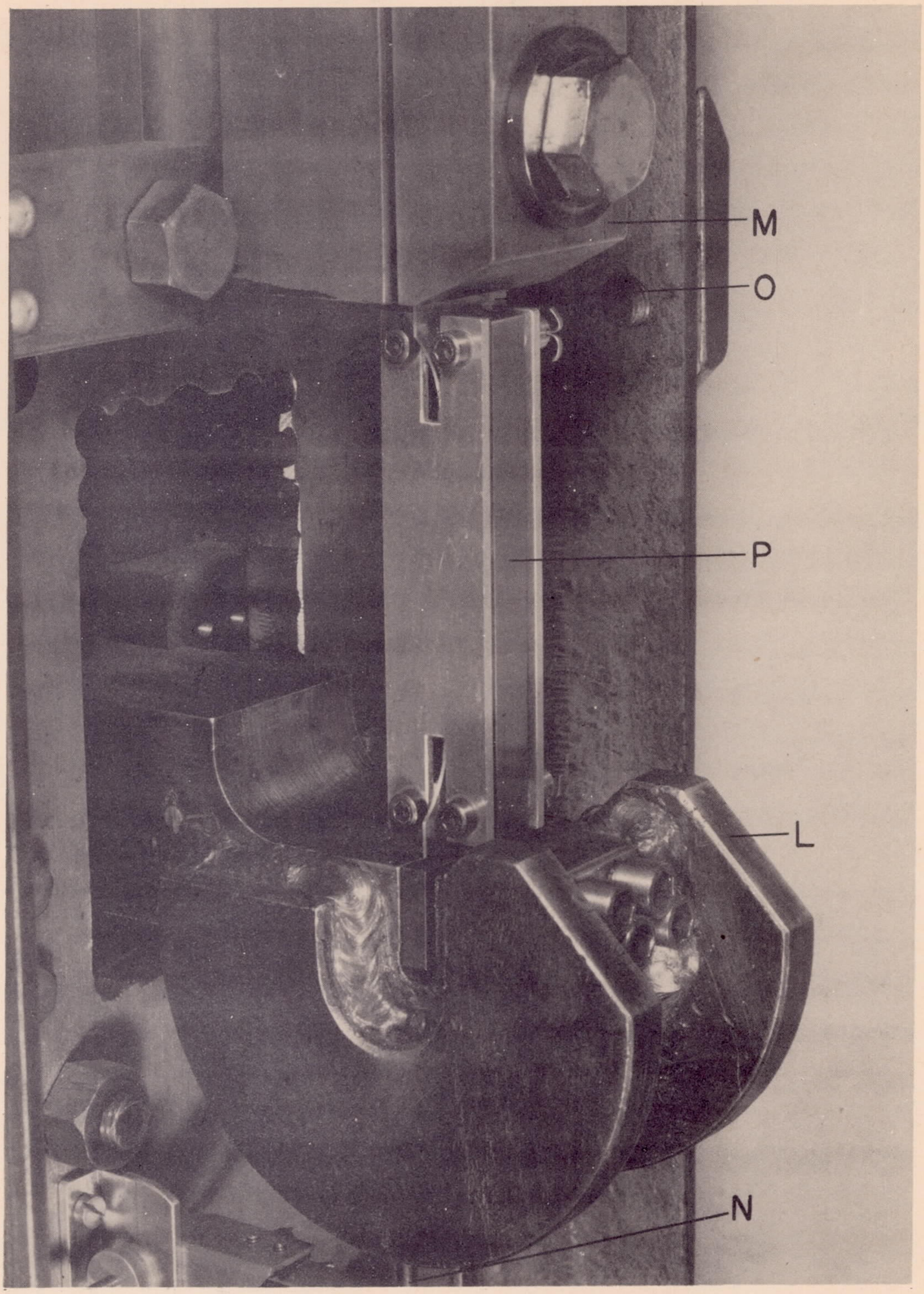

Figure 3.- Jaws of machine a; a sheet-metal specimen O equipped with lateral guides P is in place.

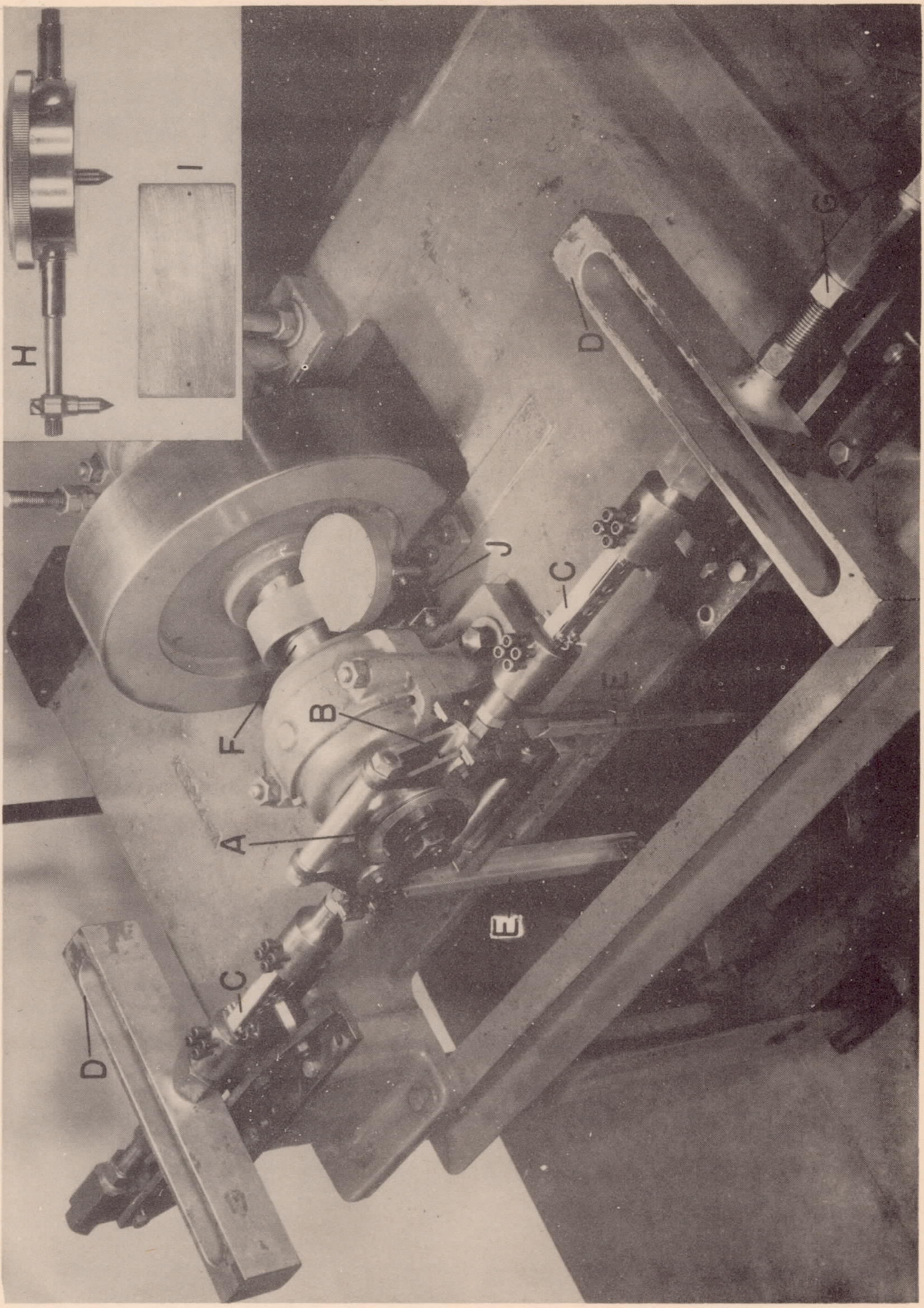

Figure 4.- Machine b.

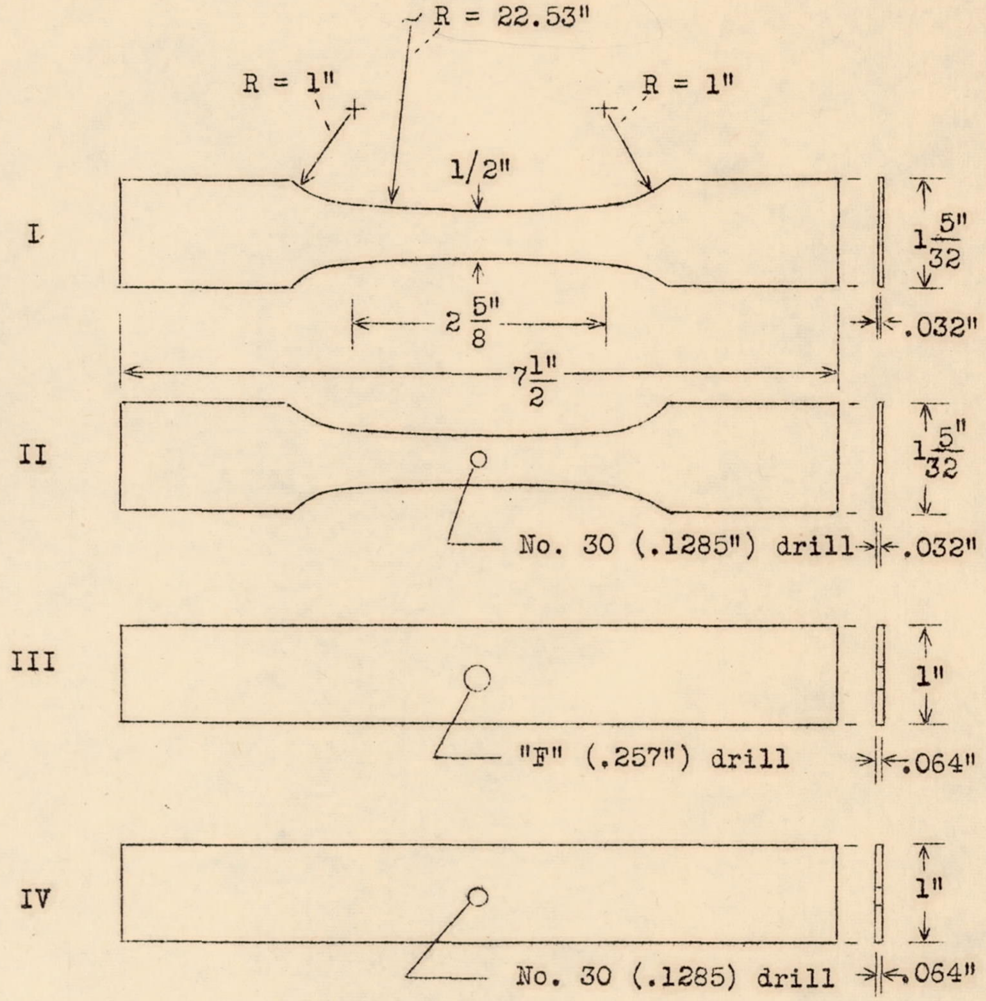

Figure 5.- Drawing of fatigue specimens.

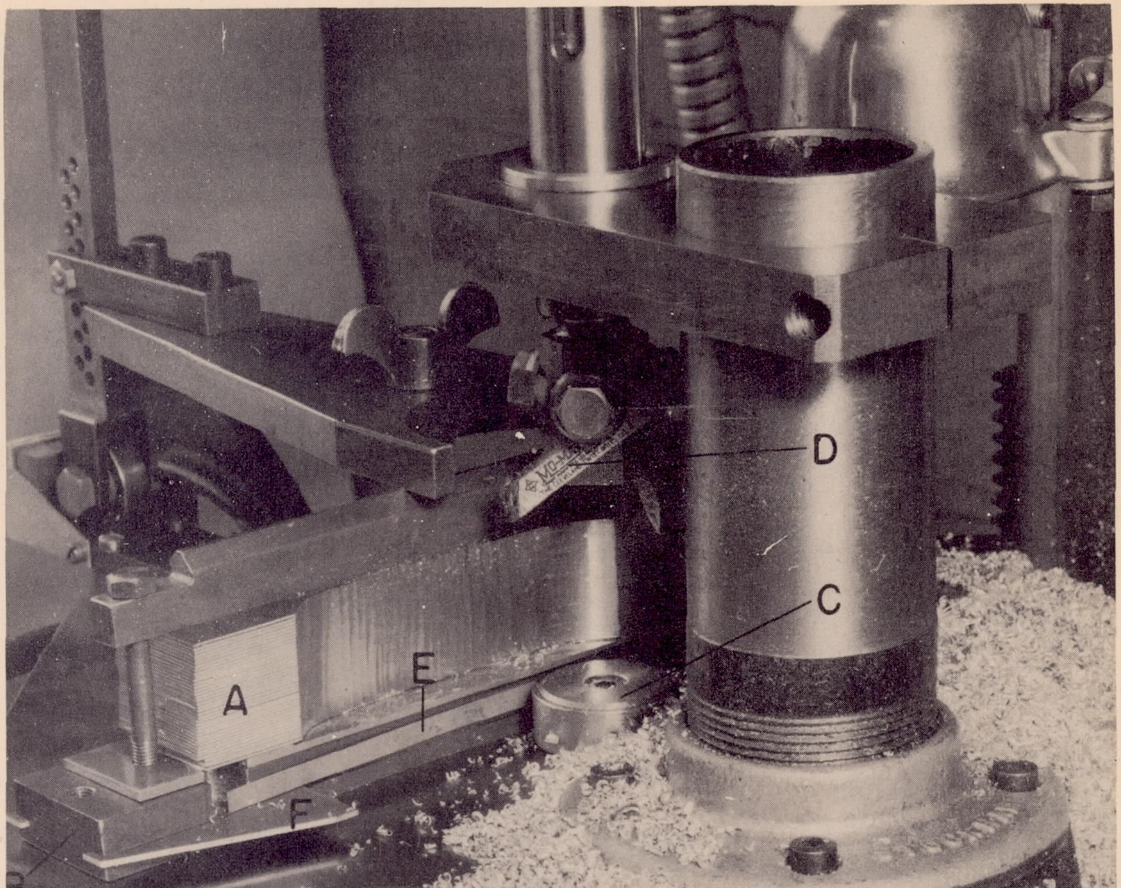

Figure 6.- Apparatus for machining reduced-section specimens.

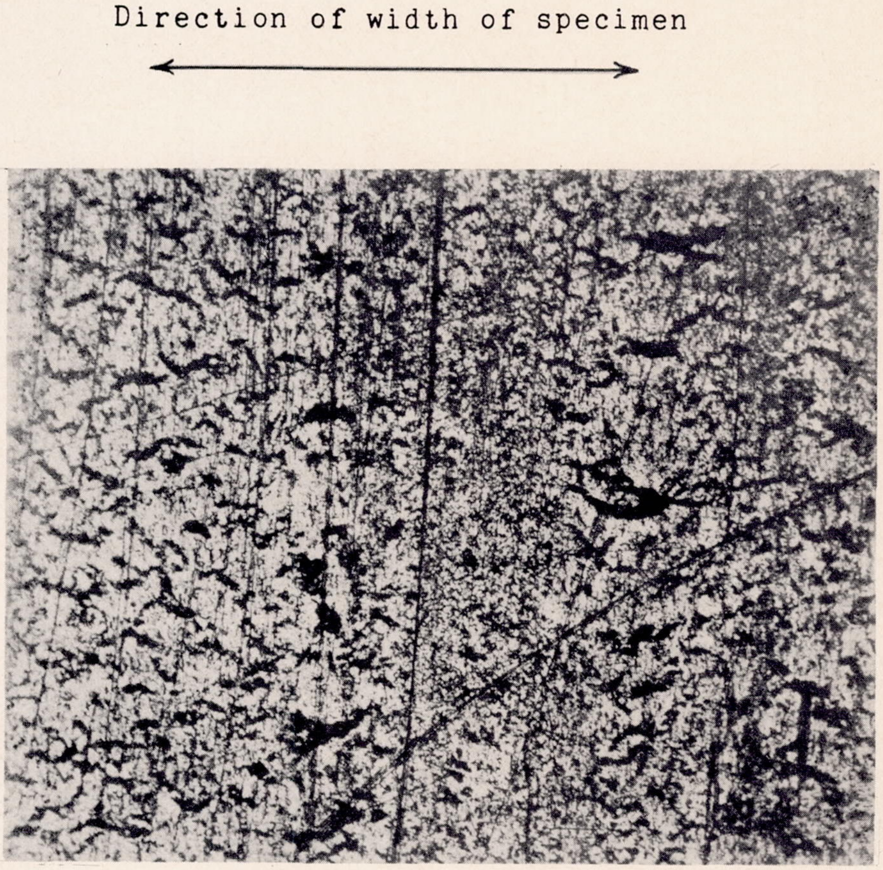

Figure 7.- Surface of sheet A, x50, showing transverse fissures.

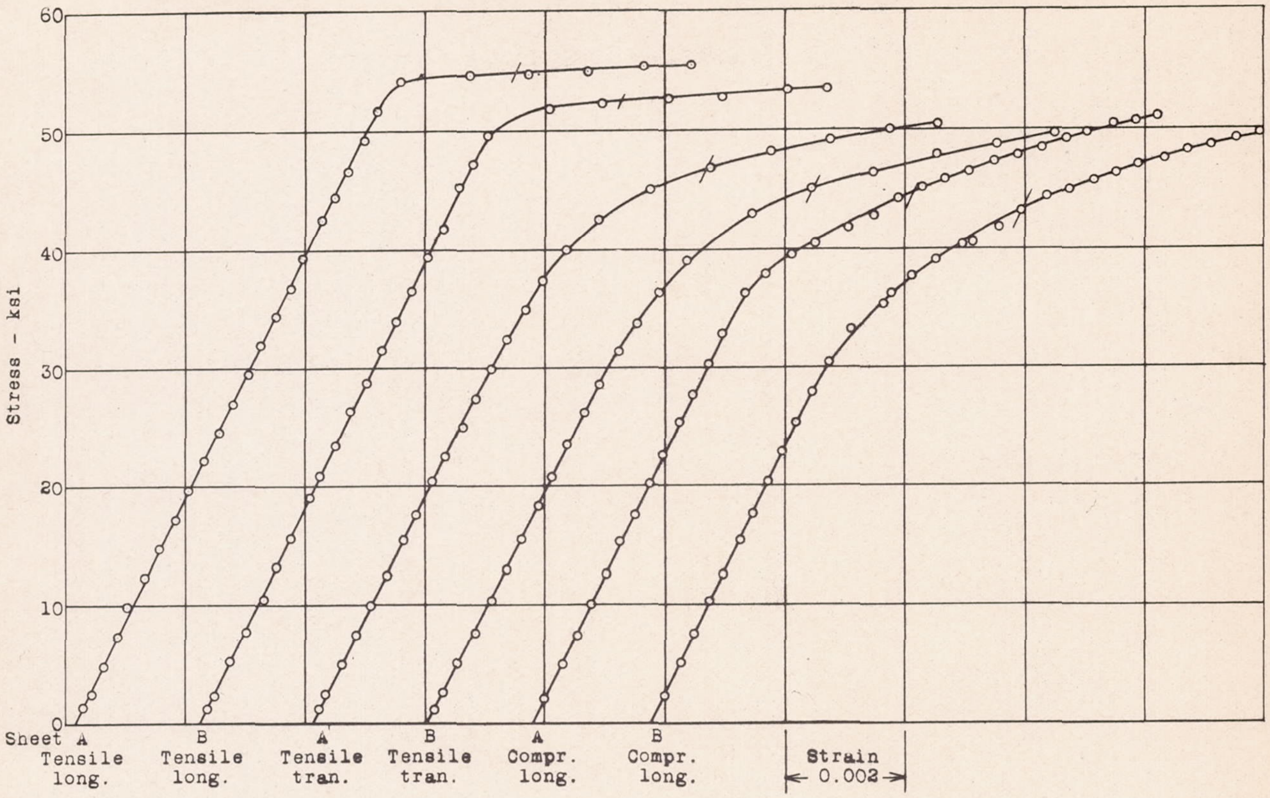

Figure 8.- Typical tensile and compressive stress - strain curves for sheets A and B, 0.032 - in. 24 S-T aluminum alloy sheet.

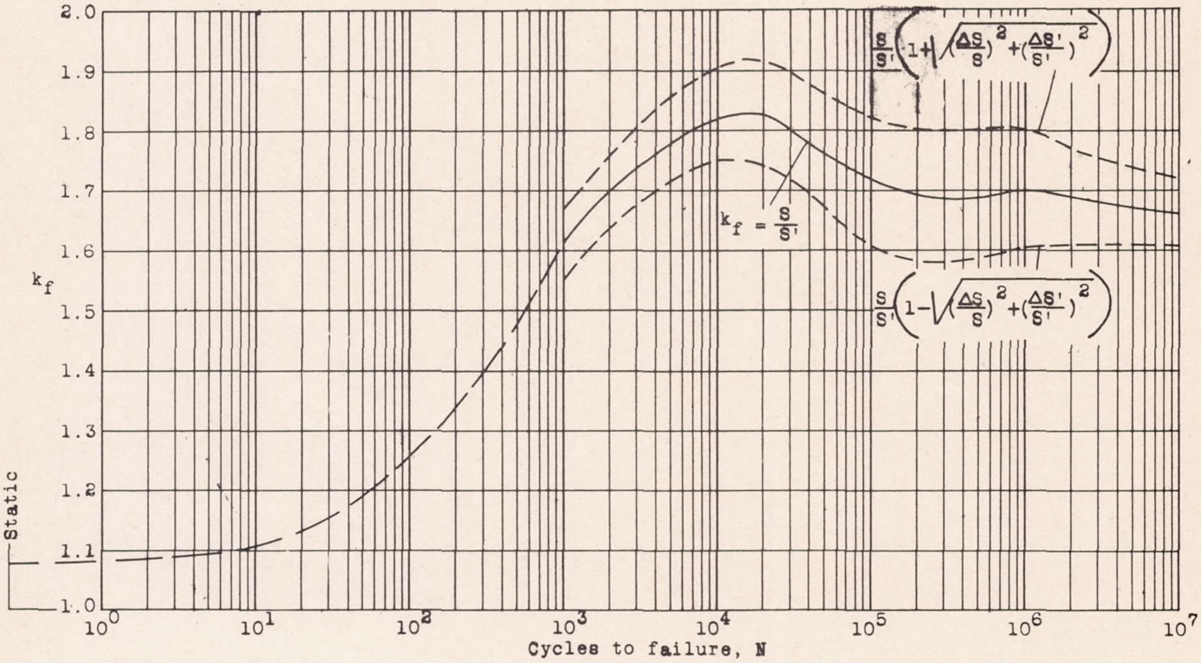

Figure 10 - Fatigue stress-concentration factor for type-II specimens.

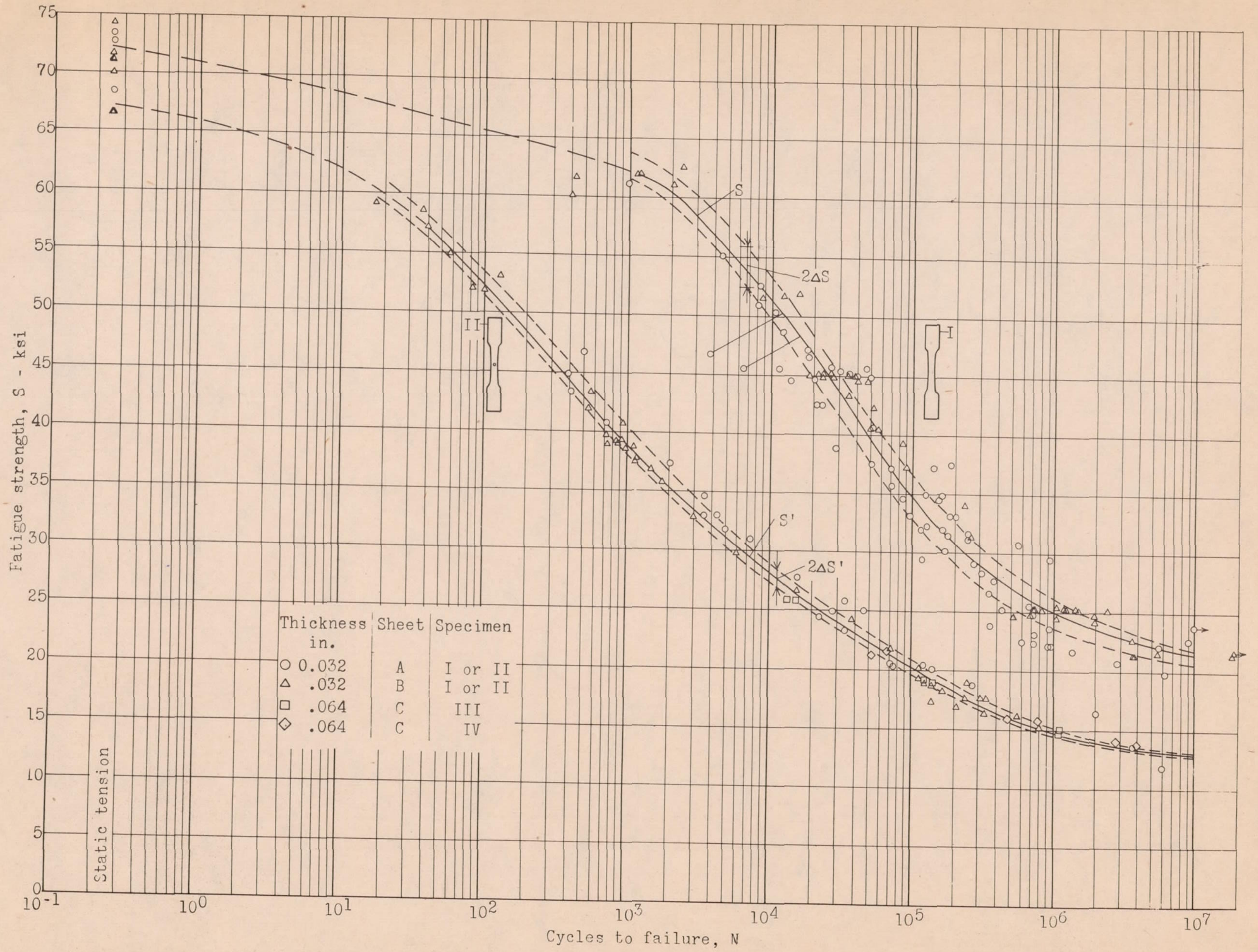

Figure 9.- S-N curves for plain and drilled specimens.