A STUDY OF STRESS CORROSION AND CORROSION FATIGUE OF ALUMINUM ALLOYS

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SUMMARY

Fatigue studies have been conducted for 24S-T alclad sheet of commercial thickness 0.051 inches. Flexure fatigue test runs were made for polished specimens, specimens subjected to corrosion simultaneously with reversed flexure, specimens previously subjected to corrosion, and specimens previously subjected to a corrosive atmosphere while in a stressed condition. The latter two cases will be called prior corrosion and prior stress corrosion, respectively.

Curves of applied stress versus number of cycles to failure have been plotted, and effective stress concentration factors have been calculated. The detrimental effects of the several corrosive conditions have been compared.

INTRODUCTION

The development of high ultimate strength aluminum alloys having less than a proportional increase in fatigue strength, combined with the development of airplanes with greater speeds, greater wing loadings, etc., have resulted in failure of many structural members by the action of fatigue. These factors have given rise to higher dynamic loads, resulting in frequent high peak stresses, and thus greater susceptibility to fatigue failure. Experiments indicate fatigue failure is hastened by the presence of a corrosive atmosphere. Authorities disagree as to whether the primary cause of these failures is stress corrosion, corrosion fatigue or a combination of both.[1,2,3,4]

The three general types of corrosion attack in aluminum alloys are:

(1) Surface corrosion in which a general and uniform removal of the surface layer results.

(2) Grain-boundary or intercrystalline corrosion in which the corrosive agent attacks exclusively along the grain boundaries.

(3) Pitting in which a localized penetrating attack occurs.

While surface corrosion is a pure chemical reaction, pitting and grain-boundary corrosion may be considered primarily as electrochemical.

In order to understand completely the concepts of stress corrosion and corrosion fatigue, it must be shown how each differs from other types of corrosion and from each other.

Stress Corrosion: The phenomenon of stress corrosion has been observed to occur in the alloys of practically every metal, causing serious damage, especially in the aluminum alloys used in aircraft construction. The lighter metals employed in aircraft are not the only ones that are susceptible to its ravages; the caustic embrittlement of boiler plate, the season cracking of brass, and the stress corrosion failure of steel alloys serve as concrete

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[1]Jackson, L. R., Grover, H. J., and McMaster, Battelle Memorial Institute, "Advisory Report on Fatigue Properties of Aircraft Materials and Structures", War Metallurgy Committee, OSRD No. 6600, Serial Number M-653, March 1, 1946.

[2]Arnstein, K., Shaw, E. L., "Fatigue Problems in the Aircraft Industry", Metals and Alloys, 10:203-9, 1939.

[3]"2-0-2 Report", Aviation Week, 49:26, October, 1948.

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

examples of its occurrence.

The term "intercrystalline corrosion" signifies attack along the crystal boundaries. Light alloys containing copper are well known for their susceptibility to intercrystalline corrosion. Pure aluminum and aluminum manganese alloys are not subject to this type of attack. The copper bearing alloys are heat treatable but if the heat treatment is carried out incorrectly, the tendency to intercrystalline corrosion is increased. Heat treatment of these alloys involves maintaining them at a temperature just below the solidus until they consist of one phase only. They are then quenched and the one-phase structure is retained at room temperature giving an increase in hardness. This is known as solution heat treatment.

E. H. Dix[5] found that if the heat treatment is carelessly carried out, the resulting alloy may be very susceptible to attack. This attack is considered to be associated with the precipitation of the intermetallic compounds along the grain boundaries in abnormal concentration. He found that discrete particles precipitated from the aluminum copper alloy after heat treatment and ageing for two weeks at 200° C, and that the grain boundaries precipitation was at a more advanced stage than that of the rest of the crystal.

The effect of quenching temperatures has been studied by H. S. Rawdon[6] and others who found that with aluminum alloys, the risk of intercrystalline corrosion decreased with increase of quenching temperature. The temperature

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[5]"The Corrosion of Metals, Part Eight, Aluminum and Its Alloys", Sheet Metal Industries, August, October, 1947. January, 1948.

[6]Rawdon, H. S., "Corrosion Embrittlement of Duralumin" I and II, National Advisory Committee for Aeronautics, Technical Note No. 282, 1927, and Technical Note No. 283, 1930.

of the quenching medium also had effect on attack. Quenching in cold water gave better results than quenching in boiling water.

There are three types of grain-boundary corrosion:

(1) Intercrystalline or intergranular corrosion where the attack occurs along the grain-boundary and is gradual, during which time the change in tensile properties decrease as the attack progresses. The surface of the specimen during the time of attack appears practically unaltered, but sometime does appear rough and uneven through microscopic study.

(2) Lamellar, or exfoliating corrosion, is defined as an intergranular attack which is characterized by exfoliation of thin layers parallel to the direction of forming. Elongated grains are present, the sides of which are susceptible to corrosion or the structure can consist of fine grains with only the boundaries in the direction of forming undergoing corrosive attack.

(3) Stress corrosion is a grain-boundary type of corrosion and is characterized by acceleration of attack. Specimens subjected to stress break suddenly at the point most severely attacked, and without distortion. Three conditions must exist for stress corrosion to occur: (a) A suitable corrosion medium must be present. (b) The material must be subjected to mechanical stresses. (c) The material must be in a condition suitable to corrosion.

The three types of grain-boundary corrosion occur not only in their pure forms but in numerous transition stages. In general, it can be assumed that all materials showing a tendency toward intergranular attack are susceptible to stress corrosion. In corrosion experiments the speed of penetration of intergranular and lamellar corrosion has been measured at approximately 0.01 mm/day.

Experiments on the effect of hydrogen-ion concentration have revealed that aluminum alloys can be divided into two classes which behave differently under the various treatments. The alloys of al - mg - zn have a lower potential (are less noble) than those of al - mg - cu. This observation has led to the hypothesis of a difference in solution potential between grain and grain-boundary, which is primarily responsible for stress corrosion failures. If these potential differences are decreased by suitable means, the alloy in question can be made less susceptible to stress corrosion.

In certain alloys of the al - mg - zn systems, the potential of the grain-boundary can be increased by adding certain alloys, while lowering the potential of the grains can be effected by establishing a suitable condition of stress or by appropriate heat treatment. Recent German research has revealed that the solution potential differences between grains and grain-boundaries can be lowered by the addition of stabilizers, by extra precaution in finish rolling with intermediate annealing, and by proper heat treating temperatures. All processes that cause a definite precipitation in the grain so as to equalize the potential of the grain and grain-boundary are considered satisfactory.[7,8,9,10]

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[7]Naugle, C. A., "German Theories and Accomplishments in the Field of Stress Corrosion Cracking", Technical Report, Number F-TR-1131-ND.

[8]American Society for Testing Materials, American Institute of Metalurgical Engineers, Symposium On Stress Corrosion Cracking of Metals, A.S.T.M., 1944.

[9]Evans, U. R., An Introduction to Metallic Corrosion, Edward Arnold and Company, 1948.

[10]Gough, H. J., "Crystall Structure in Relation to Failure of Metals", American Society for Testing Materials, Proceedings, Volume 33, Part II, 1933.

H. S. Rawdon[11] showed that static tensile stresses caused some increase in the corrosion of properly heat-treated aluminum alloys.

The Germans[12] examined the behaviour of various aluminum alloys subject to bending stress, both below and above the elastic limit. Even after a few days in a corrosive atmosphere those specimens which were most stressed showed fine cracks on the outer surface, which, in the case of the experiment, spread completely across the specimens. The less heavily stressed specimens took longer for the fine cracks to appear. A relationship was found between magnitude of the bending stress and the number of days before the start of the attack. Specimens with a permanent deformation without an additional elastic deformation did not break during the test, suggesting that the elastic deformation is the cause of cracking under these conditions.[13]

Some of the stress corrosion failures met in practice are due to internal stress in the material as a result of cold working operations. Cold rolling has a very strong influence in promoting stress corrosion cracking in alloys subject to this type of attack. E. H. Dix[14] examined aluminum alloys containing 6, 8 and 10 per cent magnesium. The specimens were exposed for 10 years on the roof of the American Aluminum Company and the attack was measured

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[11] Rawdon, H. S., "Corrosion Embrittlement of Duralumin and Results of Weather Exposure Tests", National Advisory Committee for Aeronautics Technical Note No. 304.

[12] Naugle, C. A., "German Theories and Accomplishments in the Field of Stress Corrosion Cracking", Technical Report No. F-TR-1131-ND.

[13] Hodges, E. S., Protective Films on Metals, Chapman & Hall, Ltd., 1932.

[14] American Society for Testing Materials, American Institute of Metallurgical Engineers, Symposium on Stress Corrosion Cracking of Metals, A.S.T.M., 1944.

by the resulting change in tensile strength and elongation. The corrosion was intercrystalline, and followed planes parallel to the surface. There was corrosion at the edges of the annealed specimens, but there was no appreciable surface corrosion. The 6 per cent magnesium alloy, after 50 per cent reduction, showed only a small loss of tensile strength, the 8 per cent showed much more, and in the case of the 10 per cent alloy practically all its strength was lost after 10 years.

He also describes the effect of preforming specimens of annealed 7 per cent magnesium alloy. Some of the specimens were bent in the form of an arc, and others had a preformed semicircle in the center and were then bent in the form of an arc. The preformed specimens cracked more easily and frequently than the others.

Corrosion Fatigue: A metal which has been subjected to corrosion or stress corrosion has its resistance to fatigue failure seriously reduced. However, this damage is far less than the reduction caused by the simultaneous action of repeated stress and corrosion, known as corrosion fatigue. In any case, the damage is due to the "stress raisers", the microscopic notches formed in the surface of the metal by corrosion. The effect of notches of all kinds has long been recognized as a major factor in causing fatigue fracture of metals, and the magnitude of the effect produced depends upon the sharpness of the notch, depth of notch, slope of walls of notch, and whether the notch is produced by cutting, by chemical action or by indentation with a blunt tool. Corrosion seems to produce a distinctly destructive type of notch, but stress-less corrosion at least under mild corrosive agents does not often produce deep notches.

If a metal is subjected to a corrosion medium while also being subjected to cycles of repeated stress, the protective film may be repeatedly broken. How fast the destructive effect progresses depends upon: (1) The rapidity of formation of cracks in the film compared with the rapidity with which the protective film can be repaired; (2) the high relative porosity of rapidly healed compared to slowly healed films; (3) the influences which tend to produce a wide spread distribution of electrochemical couples over the surface of metal, and hence relatively uniform corrosion.[15] There are many phenomena such as the change of electric potentials within the metal due to stress conditions, and the tendency of the products of corrosion to clog up the pits and delay the further spread of corrosion.

One explanation of the corrosion fatigue phenomenon that is advanced is that a pit or notch formed by corrosion is opened up when tension is applied to the piece, and becomes filled with rust or other products of corrosion. When the tension is released and the pit closes down on the corrosion products it contains, these products exert a wedge action to produce cracking. The cracks increase the local stress and matters progressively go from bad to worse. Also, repeated stress tends to crack any protective coating of a film of corrosion products and thus allow continued corrosion at the cracks. Usually the prime cause of the damage is corrosion, but the immediate cause of failure is the "stress-raiser" effect of the pits.

The first published account of laboratory experiments on corrosion fatigue is that of P. B. Haigh[16] in 1917, who found from experiments conducted

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[15]Evans, U. R., Jr., "Thin Films in Relation to Corrosion Problems", Journal of the Institute of Metals, (Brith.) Volume XLVI, No. 2, Page 7, 1931.

[16]Haigh, P. B., "Experiments on Fatigue of Brasses", Journal of the Institute of Metals, (Brith.) Volume XVIII, Page 55, 1917.

on brass and bronze subjected to alternating stress while in contact with corrosive agents, such as ammonia, salt water and hydrochloric acid, a lowering of the fatigue limit. He also points out that the damaging effect is not produced unless corrosion and fatigue are simultaneous.

Haigh discovered corrosion fatigue effect while making an effort to control the temperature of brass fatigue specimens by the use of a water stream.

In 1925, D. J. McAdams, Jr.,[17] began a very extensive experimental study of corrosion fatigue. His results, and the results of other experimenters, have developed the fact that under so mild a corrosive agent as pure water the fatigue limit is reduced much below that in air. In fact, no definite value for fatigue limit for indefinitely long life under corrosion fatigue has been found even for the ferrous metals. In case of corrosion fatigue limits, it is important to state the limiting number of cycles which were used in the test, and also the frequency of cycles of stress. If the frequency of cycles of stress is low, then for a given number of cycles there elapses an appreciable amount of time during which corrosion can get in its destructive work. Hence the endurance limit is lowered. The experiments of McAdams and others showed that corrosion fatigue limit of heat treated alloy steels is but little, if any, above the corresponding corrosion fatigue limit of ordinary low and medium carbon steels. The stainless steel group resists corrosion fatigue better than do either plain carbon steels or heat treated alloy steels. With nonferrous metals the effect of corrosion on fatigue properties is so varied

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[17] McAdams, D. J., Jr., "Corrosion Fatigue of Metals", American Society for Testing Materials, Volume 26, Part II, 1926.

that no general statement can be made.[18]

R. R. Moore[19] studied the effect of fatigue on aluminum alloys subjected to corrosion then followed by cyclic stress. The specimens were subjected to corrosion for 5 and 10 day periods. The endurance limits were decreased in both cases about 25 to 35 per cent. The difference between the effect of the 5 and 10 day corrosion was very small. The endurance limit was reduced to a minimum of 12,000 p.s.i.

McAdams found the corrosion fatigue endurance limit for aluminum alloys to be 7,000 p.s.i. for fresh water and 6,000 p.s.i. for salt water.

Probably air has a slight corrosion fatigue effect on most metals, although for the steels this effect seems to be quite small. Grough and Sapwith[20] by running tests in partial vacuum found that the endurance limit of lead was more than doubled, and the aluminum alloys showed a marked improvement.

The stress cycle diagram for some aluminum alloys tested in air does not show a definite endurance limit even after 5×10^8 cycles of stress, but continue to have a downward slope quite like the stress cycle diagram of some metals under corrosion fatigue. The tests of Gough and Sapwith show that the main corrosion factor in air is a combination of air and water vapor.

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[18] Gough, H. J., "Corrosion Fatigue of Metals", Journal of the Institute of Metals, (Brith.) Volumn XLIX, No. 2, Page 17, 1932.

[19] Moore, R. R., "Effect of Grooves, Threads and Corrosion Upon Fatigue of Metals", American Society for Testing Materials, Volumn 26, Part II, Page 255, 1926, also, "Effect of Corrosion Upon the Fatigue Resistance of Thin Duralumin", American Society for Testing Materials, Proceedings, Volumn 27, Part II, Page 126, 1927.

[20] Gough, H. J., and Sapwith, D. S., "Atmospheric Action as a Factor in Fatigue of Metals", Journal of the Institute of Metals, (Brith), Volumn XLIX, Page 55, 1935.

The actual fatigue limit, that is, the stress at which a metal will run indefinitely in a flexure machine, has never been determined for the aluminum alloys.

Johnson and Oberg[21] carried the fatigue curve beyond the point determined by previous investigators. The endurance tests were made on a plain bearing, rotating beam type machine. The material used was a duralumin type alloy. From these tests, S.N. curves were plotted and although the number of cycles exceeded 400,000,000, there was no conclusive evidence found to show that the curve ever became asymptotic.

Several of the test specimens were run to 500,000,000 cycles. In case the specimen had not failed, then the stress was increased and the specimen run to failure. Several specimen were also run at 100,000,000 and 200,000,000 cycles and then retested at higher stresses to determine whether the previous operations at low stress had injured the specimens. The results indicated that 100,000,000 cycles at a stress of 14,000 p.s.i. or less does not injure or strengthen the specimen. The specimens run to 400 x 10^6 cycle at 15,000 p.s.i. was actually injured as were specimens stressed at 14,500 and 14,000 p.s.i. and run to 500 x 10^6 cycles. These results indicate that no injury will result after 100 x 10^6 cycles at 14,000 p.s.i. but serious injury is apparent after 500 x 10^6 cycles.

In view of the possibilities of attack on some of the alloys of aluminum, sheet alloy material is frequently coated with a layer of pure aluminum. By making use of the principle of sacrificial corrosion, the pure aluminum coating

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[21] Johnson, J. B., and Oberg, T. T., "Fatigue Resistance of Some Aluminum Alloys", American Society for Testing Materials, Proceedings, Volumn 27, Part II, Page 339, 1927.

suffers the corrosion attack and will have to be almost completely removed before the attack reaches the core, allowing the core to retain its mechanical properties for a much longer period. The difference in the potentials of the various alloys is utilized in the manufacture of clad products which depend on the fact that the outer layers of metal are more anodic than the core. This tends to prevent penetration of the corrosion as already described, and also seems to prevent corrosion at cut edges. In the same way aluminum alloy rivets may be used for the riveting of more anodic materials, as the heads will be protected from corrosion by the outer layer of the material with which they are in contact. The outer layer may be either pure aluminum or an alloy which has good corrosion resistance and is anodic to the core.

Localized corrosion or pitting often occurs in aluminum and its alloys. This is usually assumed to be caused by rupture of the oxide film. Differences in the thickness of the film may give rise to potential differences which will tend to set up this attack. The environment greatly affects the case with which pitting takes place in aluminum alloys. The presence of chloride ions cause rapid localized attack, and similar attack may be found when the aluminum is in contact with certain organic materials in chemical plants.

MATERIAL

The material used in this investigation was the standard 24S-T Alclad, Army-Navy Specification AN-A-13. All specimens were cut from one sheet of commercial thickness 0.051 inch. The nominal chemical composition of the core material is as follows: 4.4 per cent copper, 1.5 per cent magnesium, 0.6 per cent manganese and the balance aluminum. The core has a surface coating of commercially pure aluminum, comprising approximately 10 per cent of the total thickness of the sheet or 5 per cent on each surface. A representative stress-strain curve of the sheet is shown in Figure 1. The values are the averages of three specimens tested in tension. The specimens used were the standard American Society of Testing Materials' Tension Test Specimens described by H. E. Davis[22] in his handbook on materials testing. The main purpose of these tests was for determination of the yield point for the particular sheet of material and for defining the pertinent mechanical properties.

THE FATIGUE TESTING MACHINE

These tests were conducted on a Sonntag Flexure Fatigue Machine, Model SF-2, with a capacity varying from 250,000 pounds per square inch on 0.025 inch sheet to 20,000 pounds per square inch on 0.25 inch sheet. The motive power is produced by a 1/4 horsepower synchronous motor operating at a constant speed of 1800 revolutions per minute. The machine is a constant repeated force fatigue machine with an eccentric mass to generate the force. By adjusting the eccentricity of the mass the force applied to the specimen may be read from a scale. The force is limited to the vertical, the side forces of the eccentric being absorbed by a pivot rod. One end of the specimen is held in a rigid pedestal, the other end clamped in the load yoke. The pedestal is adjustable for different length specimens. The machine is equipped with a microswitch which automatically shuts off the motor when the specimen breaks and a counter which registers the number of cycles to failure in a ratio of 1000 : 1.

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[22] Davis, H. E., Troxell, G. E., and Wiskocil, C. T., The Testing and Inspecting of Engineering Materials, (New York: McGraw-Hill Book Co, Inc., 1941), Page 80, Figure 48, Type B.

Detailed operation of this machine is described in previous theses[23,24] and in the instruction manual[25] furnished by the company. Photographs of the testing machine are shown in Figures 2, 3 and 4.

THE FATIGUE SPECIMENS

The specimens used in this investigation form a cantilever beam with a constant stress section between the stationary pedestal and the load yoke, allowing failure to occur anywhere along this test length. Complete dimensions and mounting details are well presented in the instruction manual[26]. Photographs of whole and fractured specimens are shown in Figure 7.

Preparation: In preparing the specimens it was necessary to be extremely careful while handling the material so that the specimens would not be marred or scratched. For this investigation the specimens were cut parallel to the direction of rolling of the sheet in order to give higher value of cycles and also to provide uniformity of tests, as this factor alone has appreciable effect on fatigue properties.[27]

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[23]Bond, A. C., "Fatigue Studies of 24 S-T and 24 S-T Alclad Sheet With Various Surface Conditions", Unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 1948, 55 PP.

[24]Duchocek, H., "A Study of the Effect of Thickness on Fatigue Strength of 24 S-T 3 Aluminum Alloy Sheet", Unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 1948, 48 PP.

[25]"Instructions for Installation, Operation, and Maintenance of Flexure Fatigue Testing Machine, Model SF-2", Manual Sonntag Scientific Company, Greenwich, Connecticut, July, 1948, 18 PP.

[26]Same as 25 above.

[27]Brick, R. M., and Phillips, A., "Fatigue and Damping Studies of Aircraft Sheet Materials; Duralumin Alloy 24 S-T, Alclad 24 S-T and Several 18:8 Type Stainless Steels", American Society for Metals, Transactions, 29:435-463, 1941.

The specimens were cut to maximum outside dimensions, then the alignment holes were drilled using a drill jig, shown in Figure 6. After the specimens were cut to size with a router jig, also shown in Figure 6, they were polished to remove all surface scratches and tooth marks of the router. The flat surfaces of the specimens were polished by machine, using a very fine polishing compound. It was necessary to polish the sides by hand. For this, crocus cloth was used backed by a hard flat surface. Every effort was made to keep the intersection of the sides of the specimen and the flat surface at right angles. This completed the preparation for the specimens tested under fatigue and corrosion fatigue. The corrosive atmosphere for the corrosion fatigue run was created by allowing plain tap water to slowly drop upon a lightweight wick in contact with the test section. In this manner a small amount of water was present during the entire loading period.

The remaining specimens were subjected to a corrosive environment prior to being tested on the fatigue machine. The corrosive atmosphere was created by placing a lightweight wick in contact with the test section with the ends of the wick extending downward about 1/8th of an inch into a container of plain tap water. Through this arrangement a small amount of water was in contact with the test section during the entire corrosion period of 27 days. A number of these specimens were subjected to bending stress during the corrosion period. The stress was applied by means of an apparatus that held one end of the specimen in a built in end condition while at the other end there was a set screw provided to set the deflection to give a predetermined stress. All these specimens were stressed at 45,000 pounds per square inch. Figure 5 showsthe apparatus used to subject specimens to static bending stress.

The decision to use plain tap water for the corrosive tests was based on two important factors. Other investigators, testing similar alloys, have found that the corrosion fatigue curves very nearly coincide when tested with either fresh or salt water as the corrosive element[28]. Also, since it was impossible to completely keep the water from contact with the operating parts of the machine, it was decided to use only fresh water. Fresh water was used for the prior corrosion and stress corrosion also so as to have a common corrosive environment for all tests.

TEST PROCEDURE

The specimen was placed in the machine in a horizontal position. One end of the specimen was fixed rigidly in the pedestal and the other end clamped in the load yoke. The desired load was adjusted by means of the eccentric mass. Once the machine was started it continued until failure of the specimen occurred causing the limit switch to automatically stop the motor.

Care was taken to be sure that the centerline of the specimen was perpendicular to the fixed mounting and that the load yoke was parallel to this mounting to eliminate the possibility of unsymmetrical loading. The eccentric mass was always set and locked prior to placing the specimen in the machine to insure no preloading of the specimen.

For each curve, the tests were begun with the highest stresses, gradually decreasing the stress in increments of about two to three thousand p.s.i. for each succeeding specimen. This allowed the approximate time of break for the

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[28]"The Corrosion of Metals, Part Eight, Aluminum and Its Alloys", Sheet Metal Industries, August, October, 1947; January, 1948.

next specimen to be estimated, and thus gave more efficient use of testing time.

The maximum stress applied to the specimen was approximately 48,000 pounds per square inch, which is slightly below the yield point. The minimum stresses were of such magnitude that the life of the specimen would not exceed ten million cycles. The lower limit giving ten million cycles was necessary from a time standpoint, as four days were required for this number of cycles. Tests at lower stresses would have required many days for each point. All the tests were continued to failure, with the exception of those which would have run beyond ten million cycles. To indicate that this value was reached without failure, a horizontal arrow to the right was drawn through the point.

DISCUSSION OF RESULTS

The results of all fatigue tests were plotted in the form of S-N diagrams. The applied stress was plotted as the ordinate versus the number of cycles, plotted as the abscissa.

Investigations to determine the fatigue properties of a material usually result in test points which form a narrow scatter band, and the results are normally presented in this manner. A curve rather than a scatter band is used here. The curve is intended to represent only a trend, and is drawn through the mean values of what appears to be the scatter band. For a true determination of the width of the scatter band, hundreds of test points would be necessary. For the purpose of this investigation, a trend curve is considered sufficient.

The curve for the polished specimens was run first as a check on the correct operation of the machine, and to establish par values. The values found were much lower than similar curves found by previous investigators[29,30]. After a thorough search for the cause of these lower values, it was finally found that the width of the test section of the specimens was 10 per cent undersize. The router jig used to process these specimens had been used to prepare specimens for previous tests. There had been a gradual wearing away of the jig template where it comes in contact with the router guide. This had caused the reduction in the width of the specimens' test section. After the correction was made to the applied stress so that it corresponded to the actual area of the test section, the curves agreed favorably with the curves of previous tests.

The thickness of a number of specimens was checked with a micrometer. Although all specimens were cut from the same sheet of material, there was a small variation in thickness. The thickness of the specimens checked varied from 0.0508 inches to 0.0514 inches, giving a total variation of six ten thousandths of an inch. If the thickness of a particular specimen was one of the extreme values, the maximum error in the stress calculations would be approximately one per cent. Also, the variation in thickness was probably due in part to variation in the thickness of the clad material, which is pure aluminum and has a relatively low strength. The error would be smaller than

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[29] Brick, R. M., and Phillips, A., "Fatigue and Damping Studies of Aircraft Sheet Materials; Duralumin Alloy 24 S-T, Alclad 24 S-T and Several 18:8 Type Stainless Steels", American Society for Metals, Transactions, 29:435-463, 1941.

[30] Bond, A. C., "Fatigue Studies of 24 S-T and 24 S-T Alclad Sheet With Various Surface Conditions", Unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 1948, 55 PP.

the one per cent first calculated. When the thickness of a specimen was measured with the micrometer, the surface of the specimen was marred regardless of preventative care taken. As the normal scatter of fatigue results is much greater than the possible error of one per cent, this error was considered negligible and the commercial thickness of 0.051 inches was used in the stress calculations of all specimens.

The stress calculations are shortened and simplified by the use of Graph 90446-S in the instruction manual[31], which gives the bending stress in the specimen per pound of force for various thicknesses of specimen. This curve is merely an adaptation of the familiar beam formular,

$$f = \frac{Mc}{I}$$ [32]

where f = unit normal stress in p.s.i.

M = bending moment on the cross-section in in.-lbs.

I = moment of inertia of section about its neutral axis in inches^4.

c = distance parallel to the plane of bending between the extreme fiber and the neutral axis, or one-half the thickness in inches.

This formula may be modified to include the force of the eccentric mass and may be written:

$$f = \frac{Plc}{I}$$

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[31]"Instructions for Installation, Operation, and Maintenance of Flexure Fatigue Testing Machine, Model SF-2", Manual Sonntag Scientific Company, Greenwich, Connecticut, July, 1948, 18 PP.

[32]Niles, A. S., and Newell, J. S., Airplane Structures, Second Edition, Volumn 1, (New York: John Wiley & Sons, Inc., 1938), Page 143.

where P x l = M

P = force of the eccentric mass in pounds.

l = the distance in inches from the load yoke to the point in question on the test section of the specimen.

There is a considerable degree of scatter in the experimental points in all the curves. It should be noted that other experimental fatigue tests show a similar scatter[33,34]. There are several possible reasons for the scatter of points, some being as follows: (1) slight differences in adjustment of the machine and setting of the required load; (2) slight differences in machining and finishing the specimen; (3) metallurgical differences in the samples; (4) the effects of work hardening; (5) the slight differences in thickness, and possibly of greatest importance; (6) the actual nature of the fatigue phenomenon.

In all the tests run there was no indication of an endurance limit. Many other investigators have run tests on aluminum and its alloys at stress levels resulting in several hundred million cycles without evidence of a well defined endurance limit[35,36].

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[33] McAdams, D. J., Jr., "Corrosion Fatigue of Metals", American Society for Testing Materials, Volumn 26, Part II, 1926.

[34] Johnson, J. B., and Oberg, T. T., "Fatigue Resistance of Some Aluminum Alloys", American Society for Testing Materials, Proceedings, Volumn 27, Part II, Page 339, 1927.

[35] McAdams, D. J., Jr., "Corrosion Fatigue of Nonferrous Metals", American Society for Testing Materials, Proceedings, Volumn 2, 1927.

[36] Gough, H. J., and Sapwith, D. S., "Atmospheric Action as a Factor in Fatigue of Metals", Journal of the Institute of Metals, (Brith.), Volumn XLIX, Page 93, 1932, Also Volumn XLVI, Page 55, 1935.

During the testing of the specimens it was noted that after a certain time, depending upon the stress, a large number of cracks in the weak aluminum coating began to appear. The cracks probably propagated into the alloy core and hence produced failure. Such cracks appear to be due to yielding of the surface coating under reversed stress and are inherent to alclad material[37]. This phenomenon can be clearly seen in Figure 7 on the three fractured specimens.

Microscopic study of the polished specimens before testing revealed numerous scratches and marks on the surface despite the polishing and careful handling of the material. Study of the surface of the specimens after the test showed the inherent cracks of the pure aluminum clading material to be similar in appearance to a "cobble stone" street. The rises and depressions were more of an oval shape rather than sharply defined cracks. At high stresses the ovals were completely rounded, while at low stresses the crests of the ovals tended to have flat surfaces. These cracks did not penetrate the clad material except at the point where the specimen actually failed. Microscopic study of the cross section of the fracture revealed a small area of smooth surface, where the initial crack formed. The remainder of the section appeared fibrous thus showing the effects of tear during rapid failure, which is similar to what is observed in a tension break. In Figure 7, specimen (a) is a polished specimen before testing. Specimen (c) is a fractured polished specimen.

Fatigue runs were made on specimens subjected to a corrosive environment for 27 days prior to being tested. A comparison of these results with the

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[37]Bond, A. C., "Fatigue Studies of 24 S-T and 24 S-T Alclad Sheet With Various Surface Conditions", Unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 1948, 55 PP.

results of fatigue runs on polished specimens can be seen in Figure 8. This would cause one to believe that the specimens suffered an appreciable amount of corrosion. Microscopic study revealed that there was no corrosion present; however, there was a considerable amount of stain or foreign matter. This can be observed on specimen (b) in Figure 7. This indicated that the presence of the foreign matter was the cause of the lower values. This was proven to be the case as several specimens were polished after the corrosive application, then tested. The values found from specimens thus processed were very close to the values found for the polished specimens without previous corrosion.

Microscopic study of the fractured specimens subjected to prior-corrosion without later polishing, revealed that the inherent cracks were filled with foreign matter. The presence of this matter in the cracks probably produces a wedge action effect that would hasten failure.

Figure 9 shows the comparison of fatigue tests of polished specimens and specimens subjected to prior stress of 45,000 p.s.i. simultaneously with corrosion. The results indicate that the phenomenon of stress corrosion has occurred. Microscopic study of the surface of the specimens prior to testing showed no evidence of stress corrosion. As in the case of the specimens subjected to prior corrosion there was foreign matter present. This matter was readily removed by polishing. Several specimens were polished after stress corroding and then tested. The values found from these specimens were only slightly higher than the values found from the prior stress corroded specimens without polishing. It is therefore believed that the high stress that the specimens were subjected to while in the corrosive atmosphere is the main cause of the decrease in life. Microscopic study of the surface of the specimen that had been in tension during the stress corrosion period revealed many surface cracks that penetrated the coating other than the one which eventually caused failure. These cracks were not present on the surface that had been in static compression prior to testing. Specimen (e) in Figure 7 is a fractured specimen that had been subjected to stress corrosion before testing for fatigue life. The foreign matter is still visible at the wide end of the test section.

The serious detrimental effects of corrosion fatigue on 24 S-T alclad can be seen in Figure 10, where results from tests on polished specimens under fatigue and corrosion fatigue conditions are presented. As shown, this effect is present throughout the range of testing. Results from investigations on unclad 24 S-T sheet show a similar effect for high values of stress; but show a much greater effect of the corrosive atmosphere at low values of stress[38]. A possible explanation of this variation is that at the high values of stress the coating is actually ruptured after a few cycles on the alclad material. Once the protective coating is broken, the corrosion is able to attack the core immediately. At lower values of stress, although the pure aluminum coating is still stressed above the yield point, there is not an actual rupture for an appreciable number of cycles. The core is not subjected to attack until the coating is completely penetrated, and therefore retains its strength much longer than an uncoated sheet would.

When subjected to corrosion fatigue, alclad materials show a much smaller reduction in the relative fatigue limit than the uncoated materials do. This does not prove that the alclad material has a greater fatigue strength

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[38]Cliett, C. B., "A Study of Fatigue and Corrosion Fatigue for 24 S-T Aluminum Alloy Sheet", Unpublished Master's Thesis, Georgia Institute of Technology, Atlanta, Georgia, 1950, 37 PP.

than plain materials do. Actually the plain 24 S-T sheet is much stronger at the values of high stress than the 24 S-T alclad sheet of same thickness. At low values of stress the plain 24 S-T sheet still has a several thousand p.s.i. greater corrosion fatigue endurance limit than the 24 S-T alclad. This would imply that in these tests of short duration, the fatigue phenomenon is the principal cause of failure and the corrosion merely accelerates this. If the testing rate was much slower the corrosion would be more detrimental and the alclad material would have the higher endurance limit. Microscopic study of the specimens which failed under the phenomenon of corrosion fatigue revealed that the test sections were severely attacked. On each specimen many deep surface cracks other than the one which eventually caused failure were observed. The cracks, whose origins were at one of the many surface pits present, were filled with what appeared to be corrosion products. This was quite different from the observation on the specimens subjected to prior corrosive conditions, where the surface cracks were relatively shallow. Specimen (d) in Figure 7 was subjected to corrosion fatigue.

EFFECTIVE STRESS CONCENTRATION FACTORS

Considering the life of polished specimens tested under ordinary fatigue as reference values, effective stress concentration factors have been calculated for all tests. These factors were determined by dividing the value of applied stress for a given life of the polished specimen by the applied stress which gave an equal life for specimen tested under one of the other conditions. A comparison of these results is presented in Figure 12.

CONCLUSIONS

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

1. The presence of a mild corrosive atmosphere for a period of time less than one month in length, does not appreciably reduce the flexure fatigue strength of 24 S-T alclad sheet material. The effect of a corrosive atmosphere for longer periods was not investigated.

2. The presence of foreign matter on the surfaces of the specimens during the test period causes a decrease in the flexure fatigue properties of 24 S-T alclad sheet.

3. The flexure fatigue strengths of 24 S-T alclad sheet was seriously reduced when subjected to a high bending stress simultaneously with a mild corrosive atmosphere prior to testing.

4. The presence of a corrosive atmosphere simultaneously with flexure fatigue causes a serious decrease in fatigue strengths of 24 S-T alclad sheet.

5. Corrosion fatigue is more detrimental to the fatigue properties of 24 S-T than to 24 S-T alclad.

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APPENDIX I, FIGURES

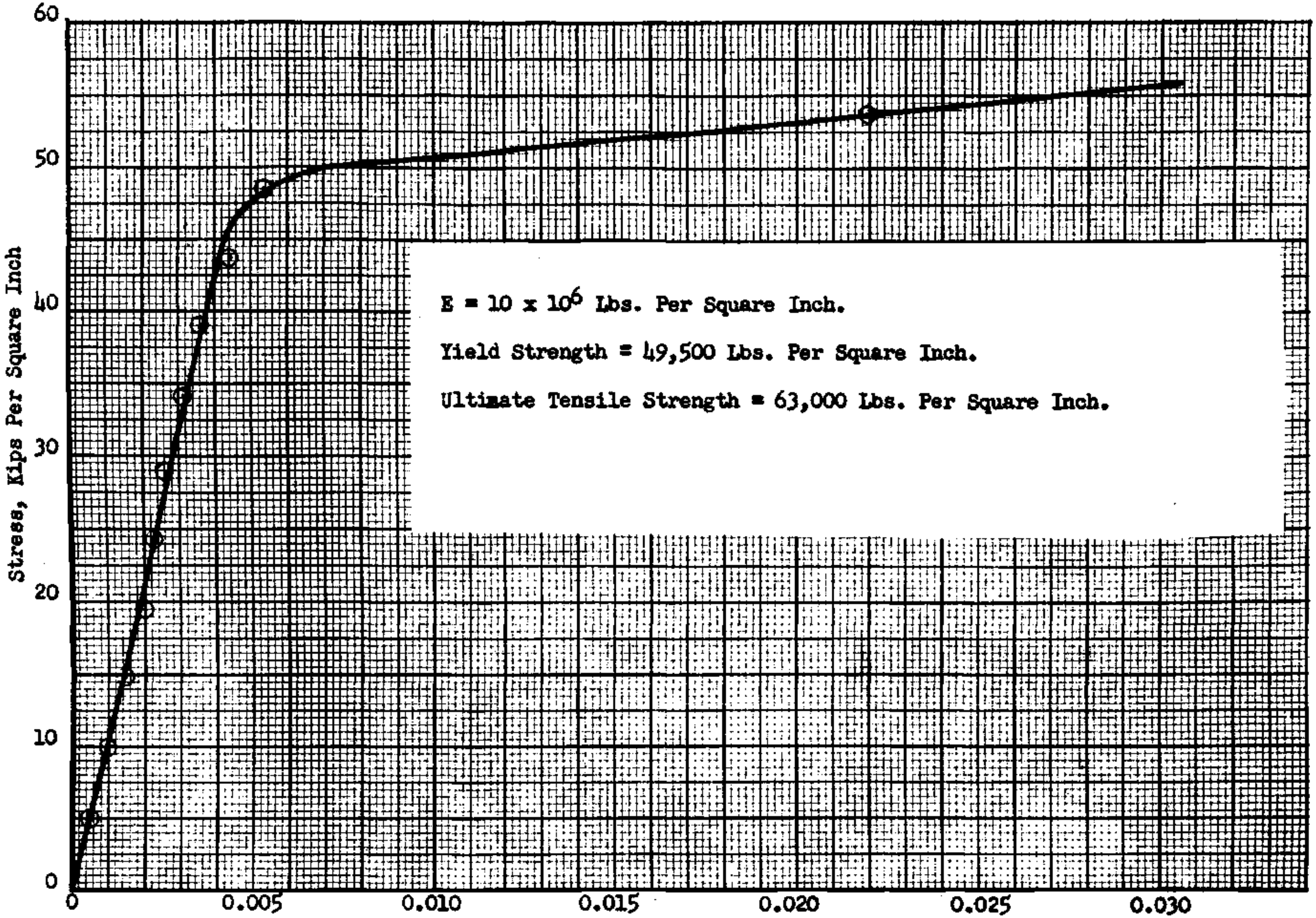

FIGURE 1. STRESS - STRAIN CURVE OF 0.051 INCH
24 S-T ALCLAD SHEET MATERIAL USED IN FLEXURE FATIGUE TESTS

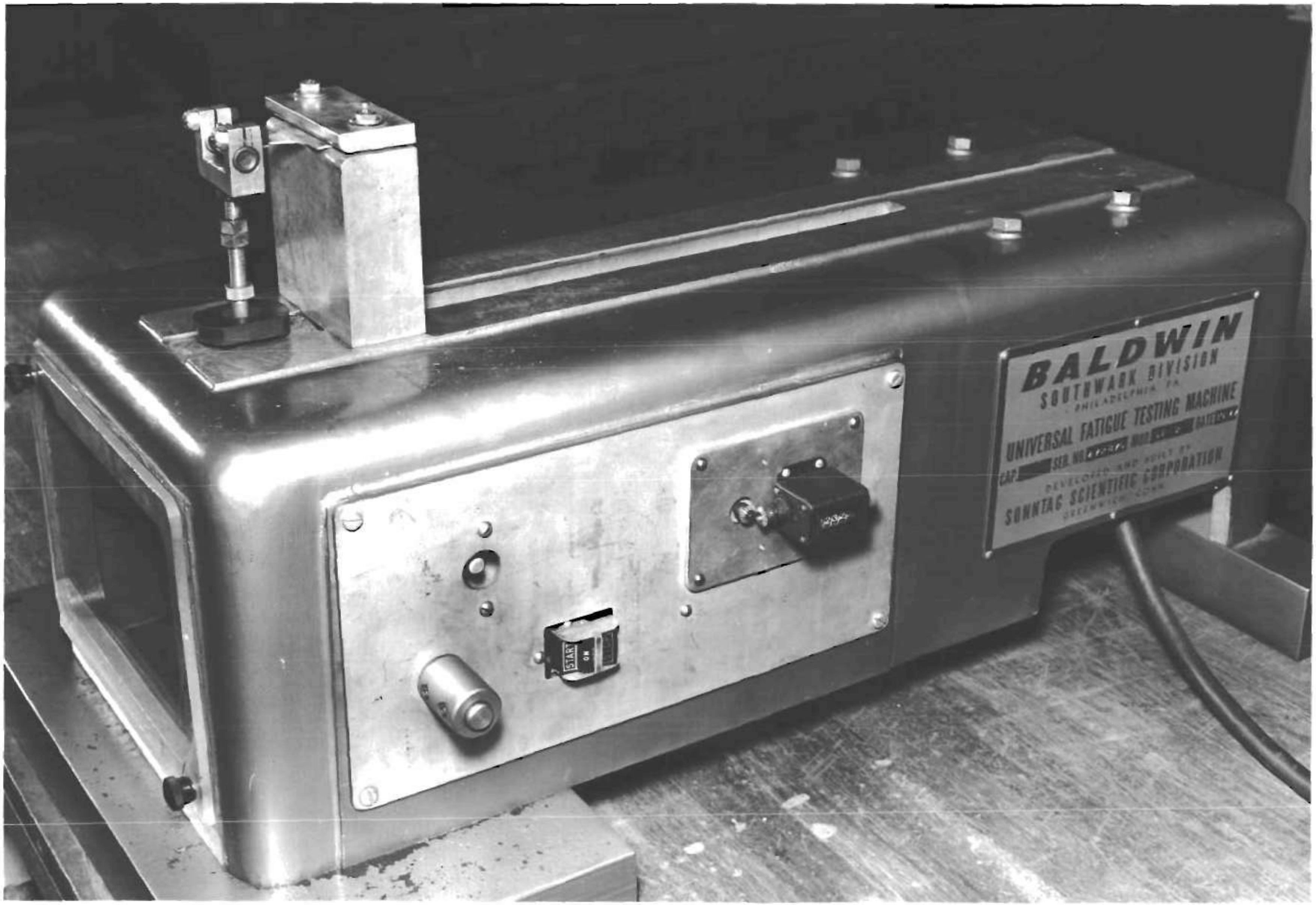

FIGURE 2. SONNTAG FLEXURE FATIGUE MACHINE, MODEL SF-2.

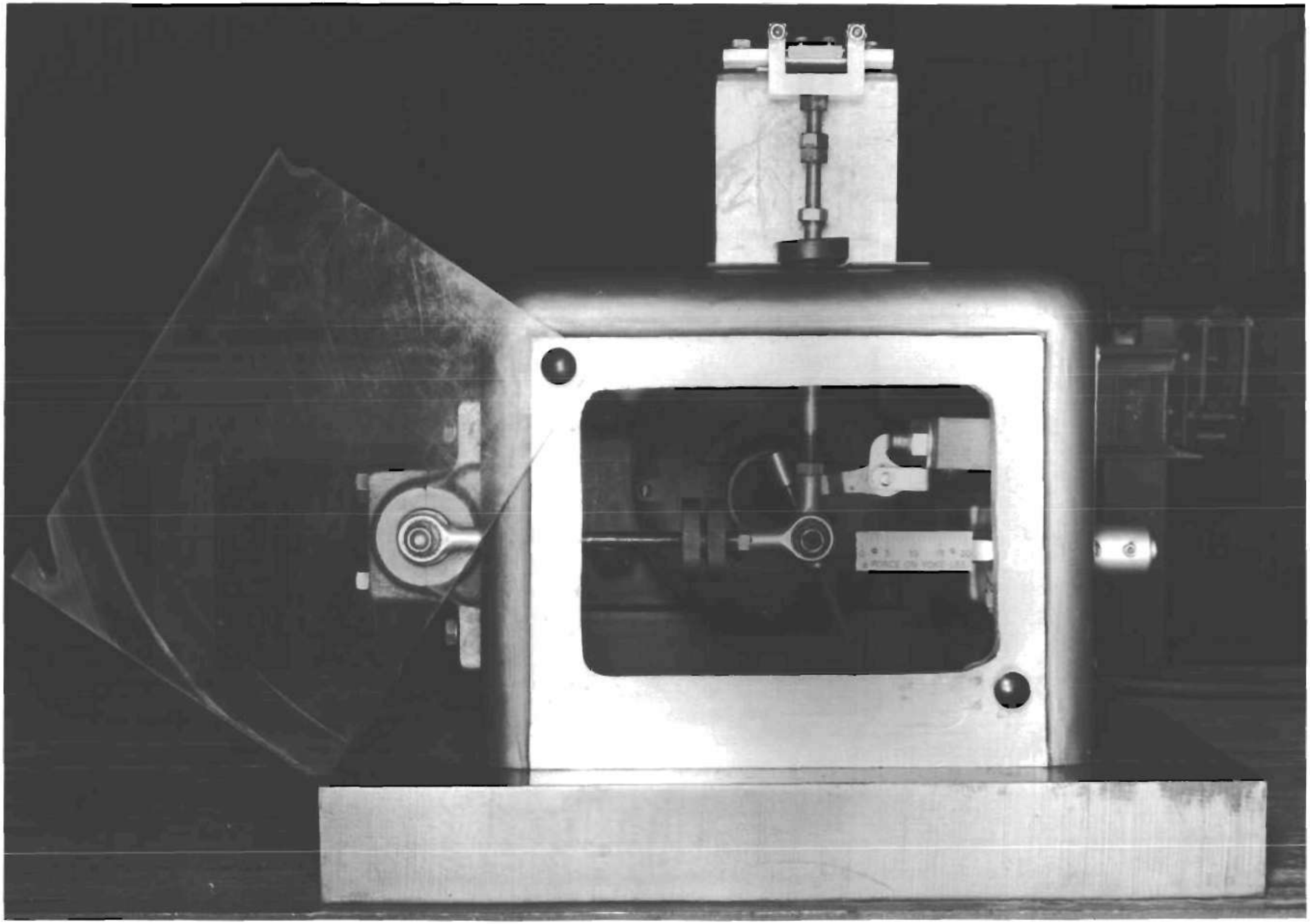

FIGURE 3. SONNTAG FLEXURE FATIGUE MACHINE, MODEL SF-2.

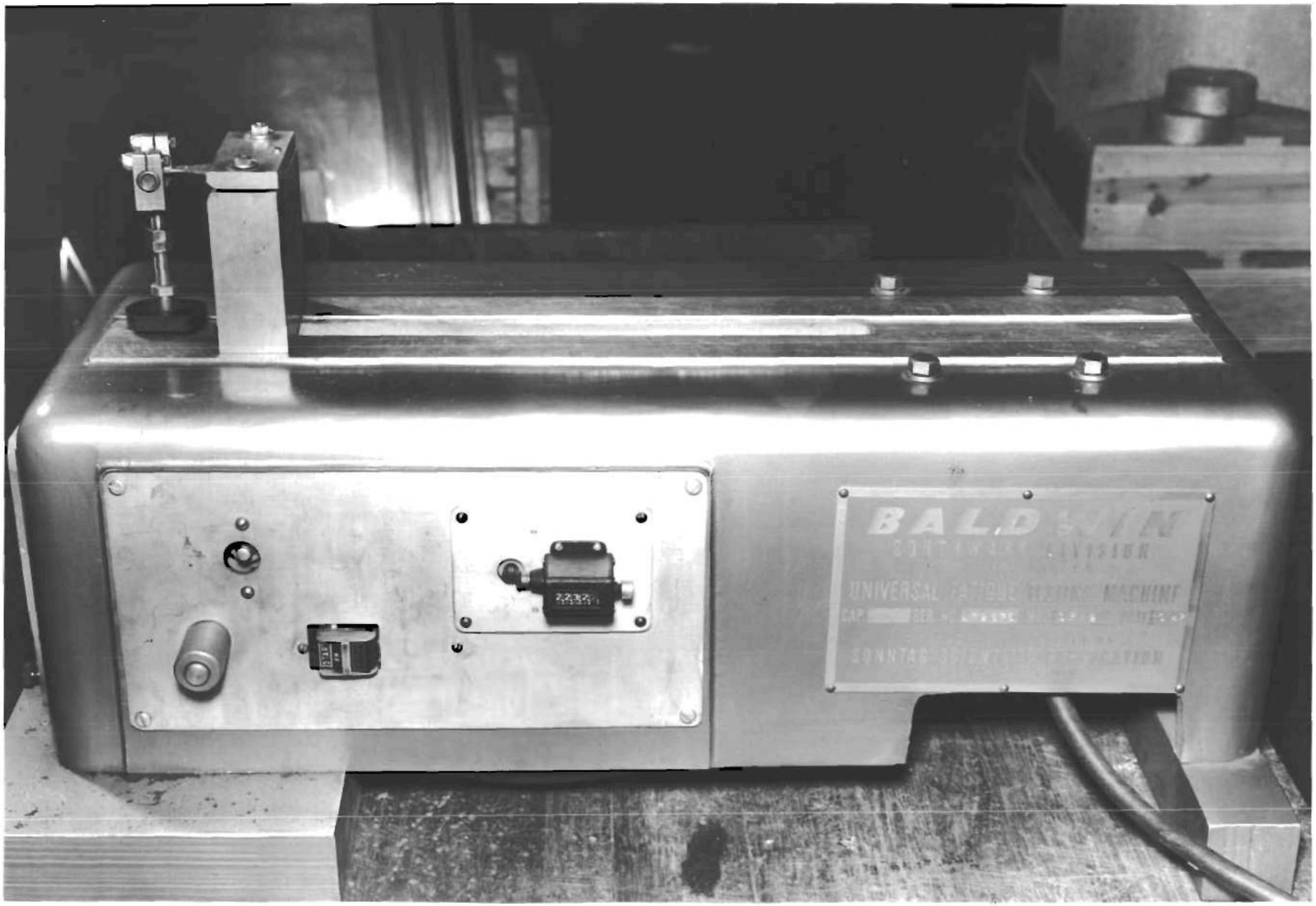

FIGURE 4. SONNTAG FLEXURE FATIGUE MACHINE, MODEL SF-2.

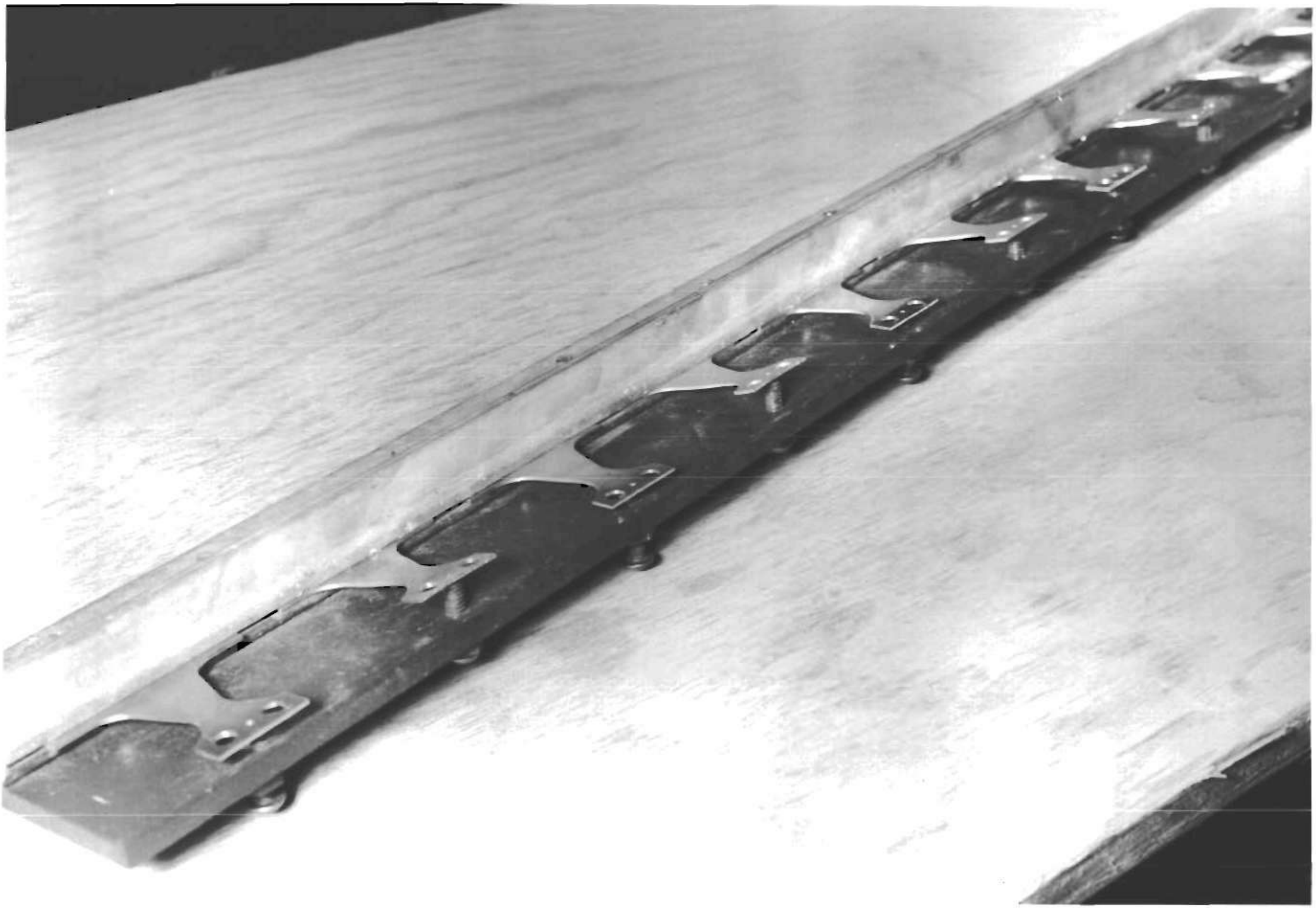

FIGURE 5. PHOTOGRAPH OF APPARATUS USED TO SUBJECT SPECIMENS TO STATIC BENDING STRESS WHILE IN CORROSIVE ATMOSPHERE.

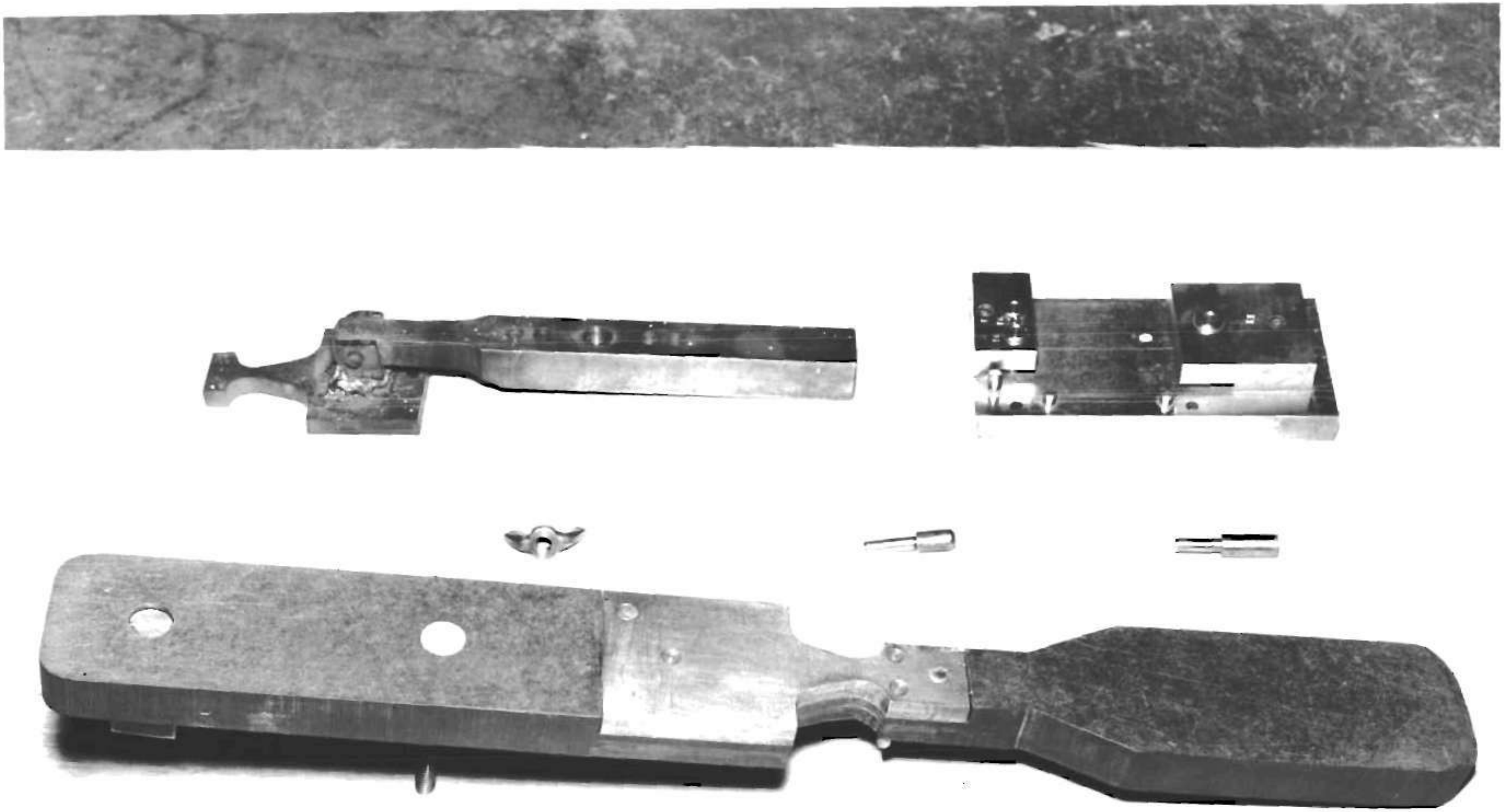

FIGURE 6. PHOTOGRAPH OF ROUTER JIG AND DRILL JIG.

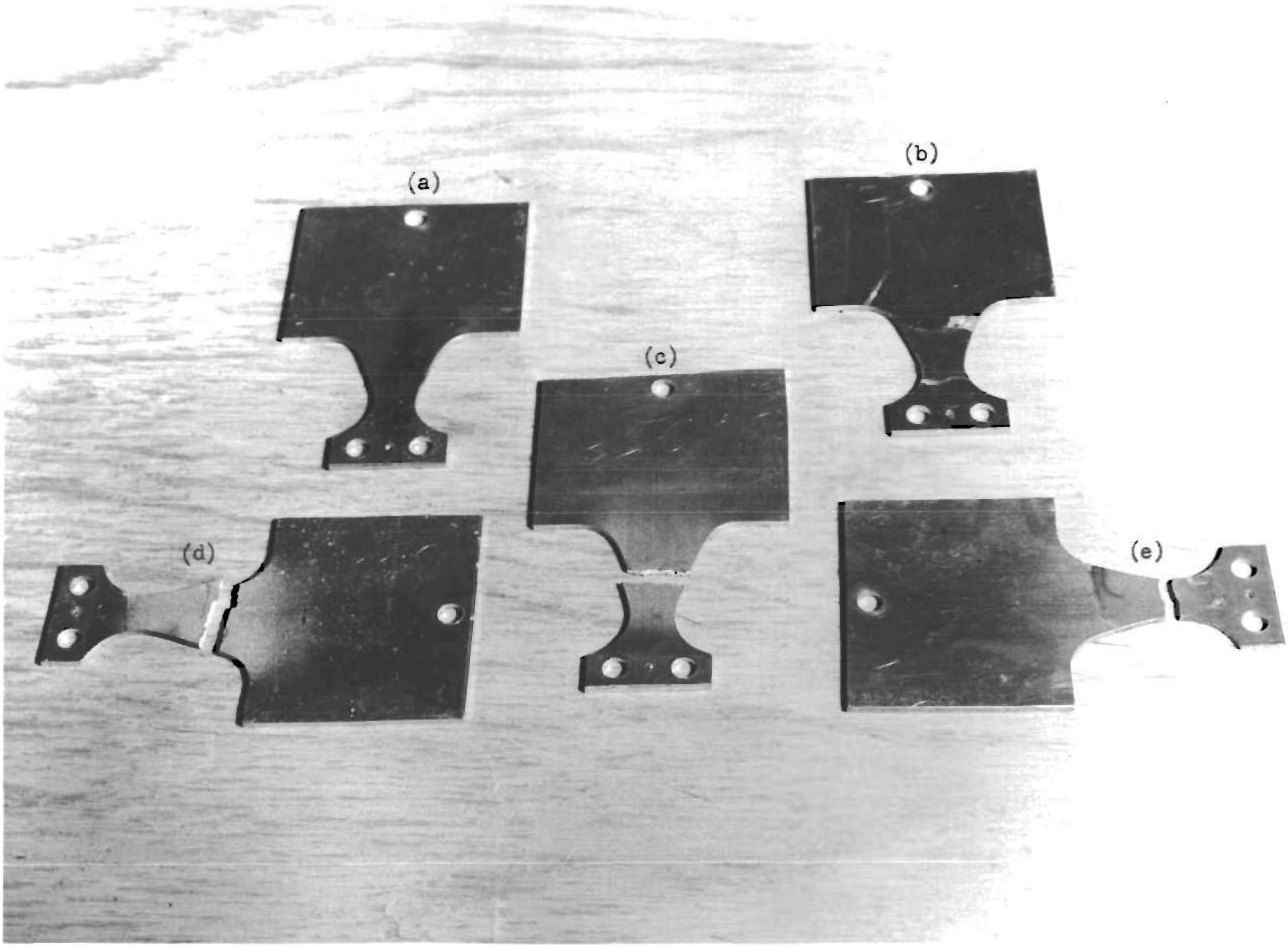

FIGURE 7. TYPICAL SPECIMENS.
(a) POLISHED SPECIMEN. (b) SPECIMEN SUBJECTED TO CORROSION. (c) SPECIMEN FRACTURED BY CORROSION FATIGUE. (d) FRACTURED POLISHED SPECIMEN. (e) FRACTURED SPECIMEN WITH PRIOR STRESS-CORROSION.

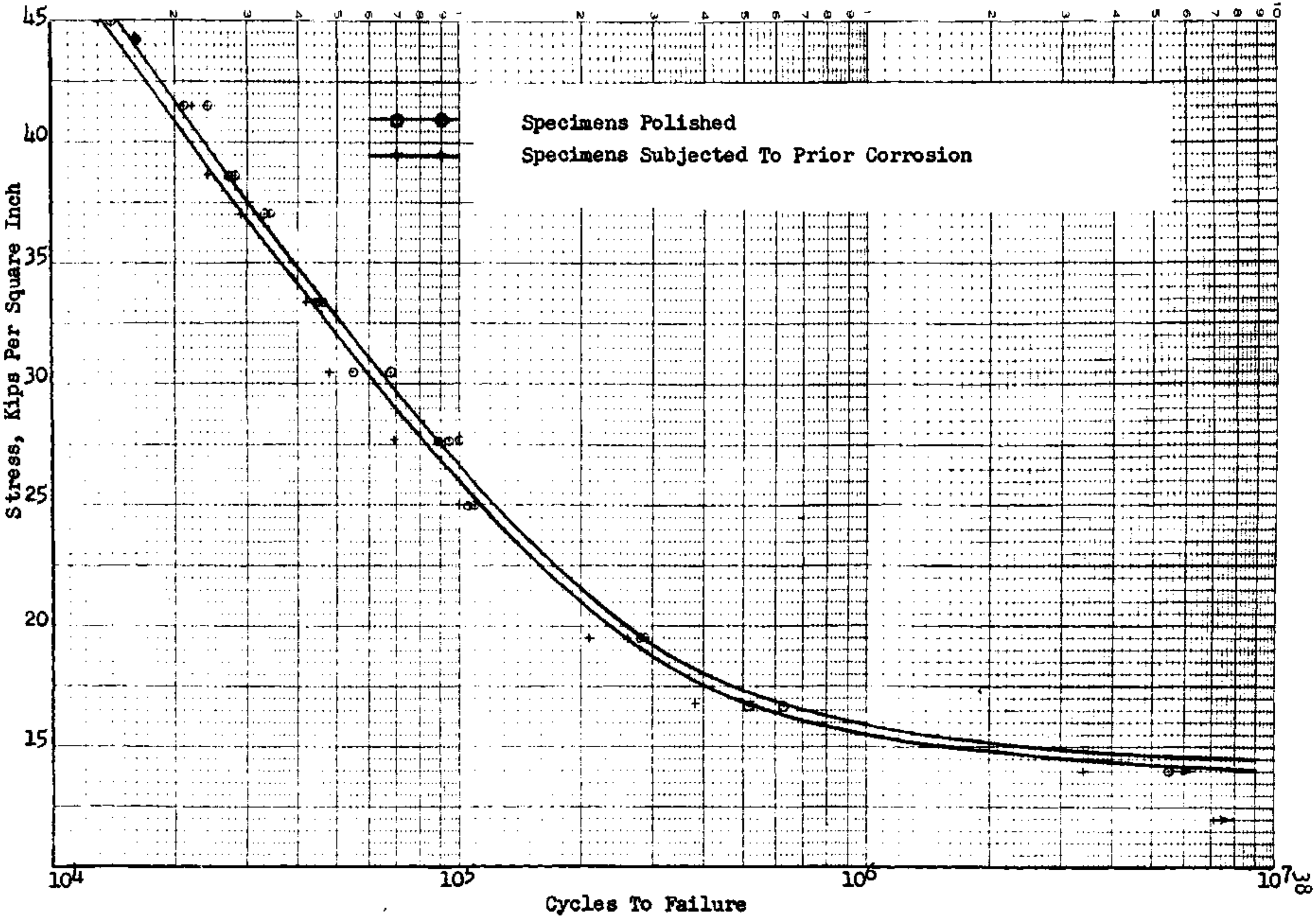

FIGURE 8. COMPARISON OF FLEXURE FATIGUE STRENGTHS OF POLISHED AND PRIOR CORRODED 24 S-T ALCLAD SHEET.

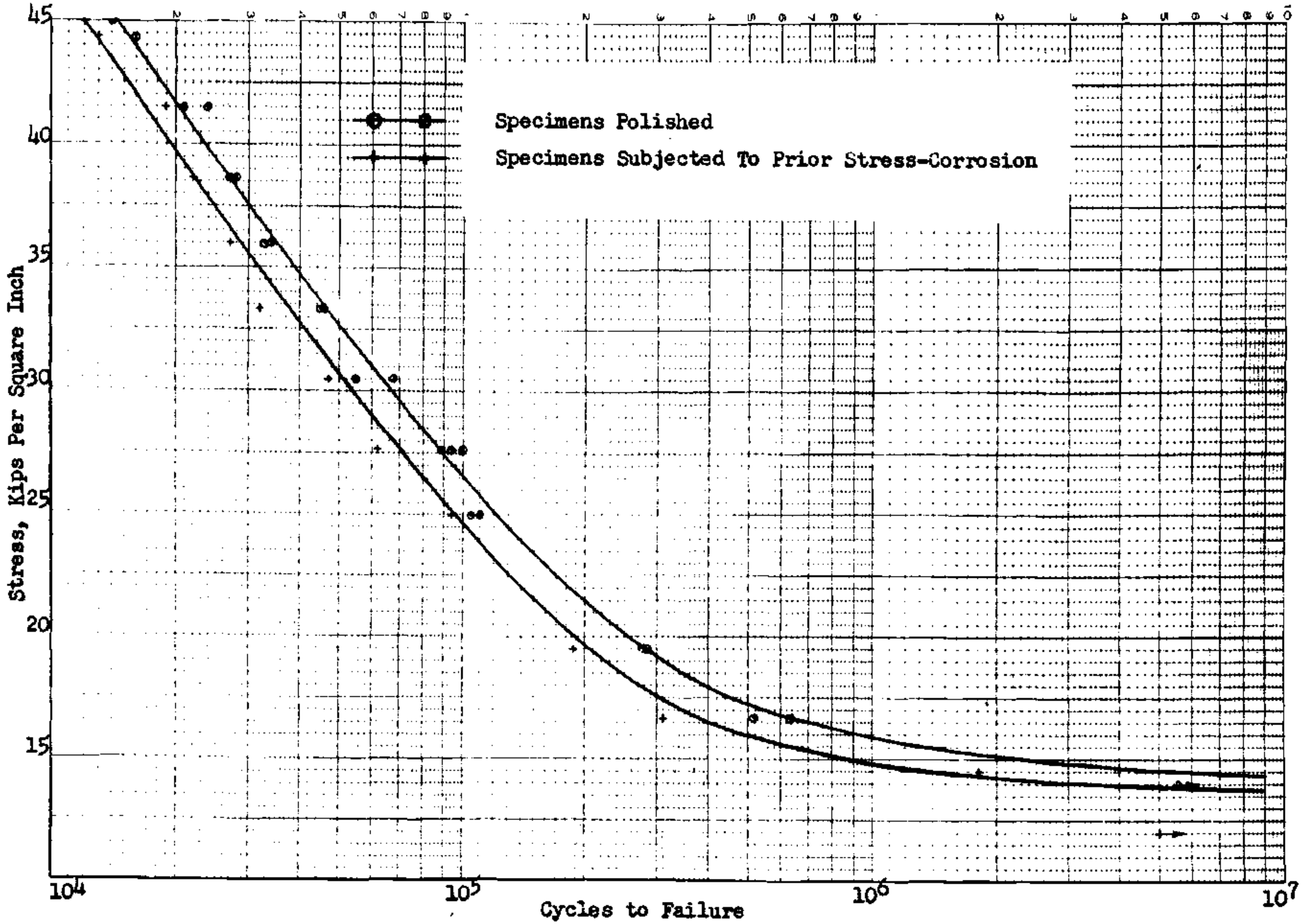

FIGURE 9. COMPARISON OF FLEXURE FATIGUE STRENGTHS OF POLISHED AND PRIOR STRESS-CORROSION FOR 24 S-T ALCLAD SHEET.

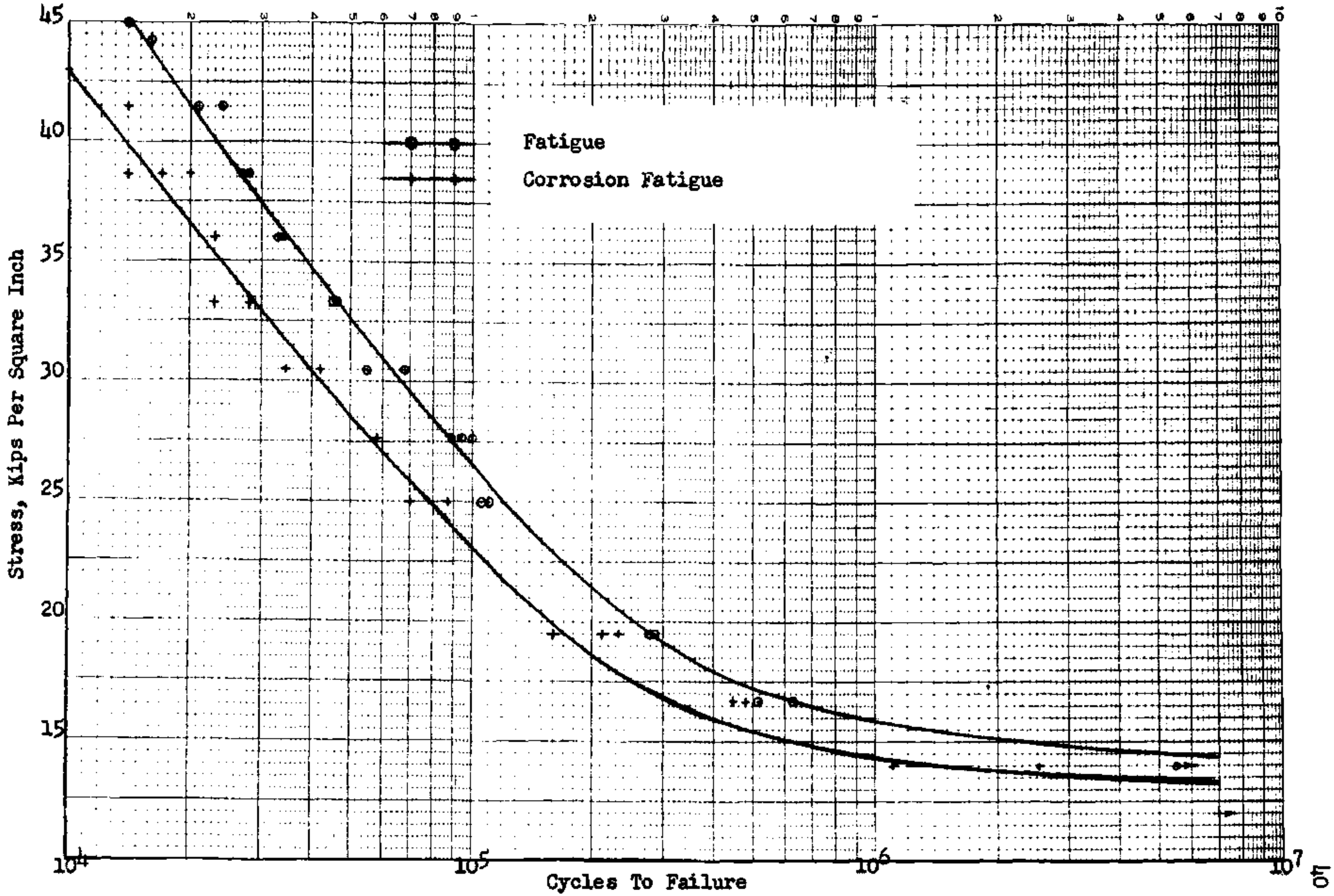

FIGURE 10. COMPARISON OF FATIGUE AND CORROSION FATIGUE FLEXURE STRENGTHS FOR 24 S-T ALCLAD SHEET.

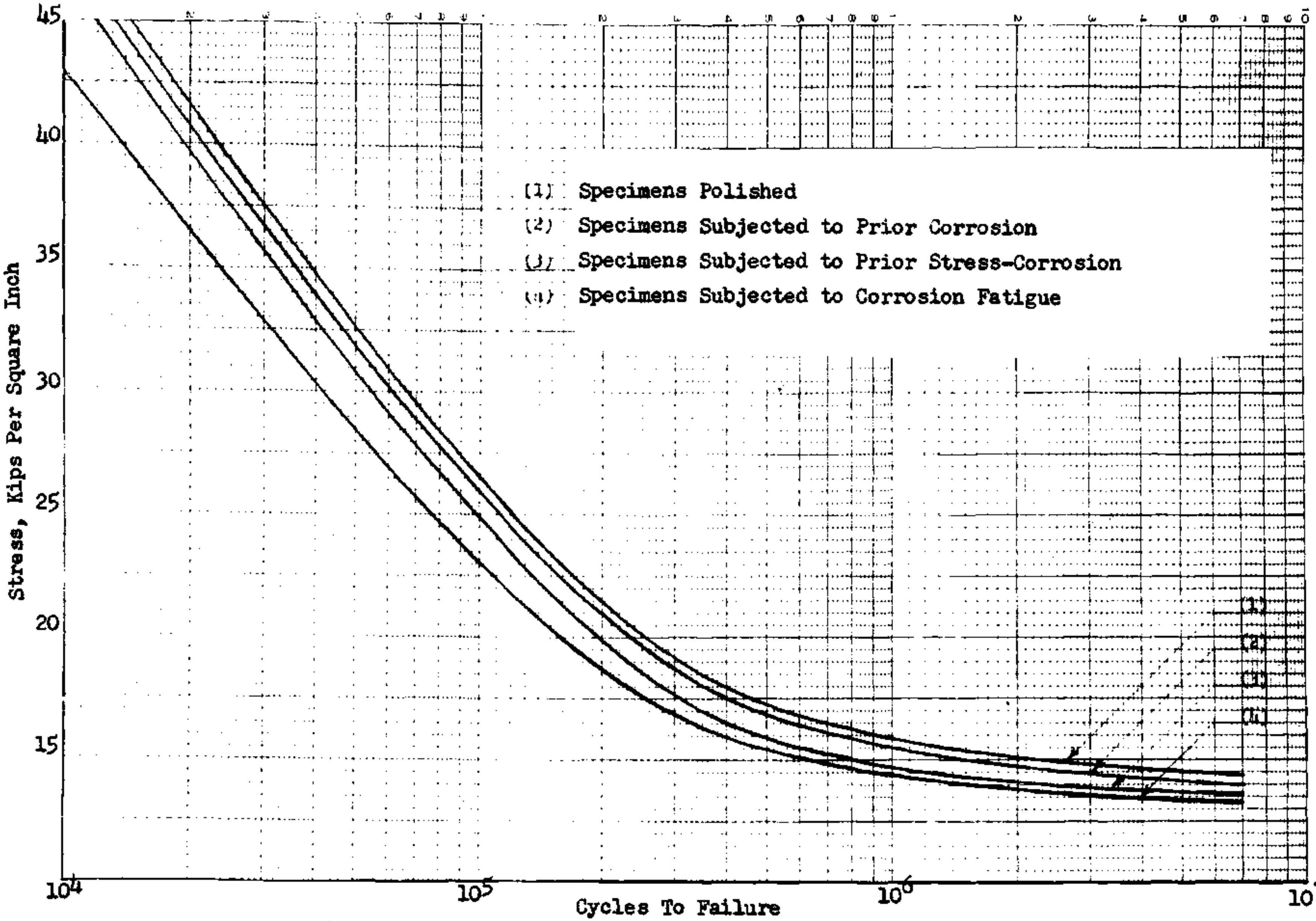

FIGURE 11. REPEATED FLEXURE FATIGUE CURVES SHOWING THE RELATIVE EFFECTS OF VARIOUS CORROSION CONDITIONS ON THE FATIGUE LIFE OF 0.051 INCH 24 S-T ALCLAD SHEET.

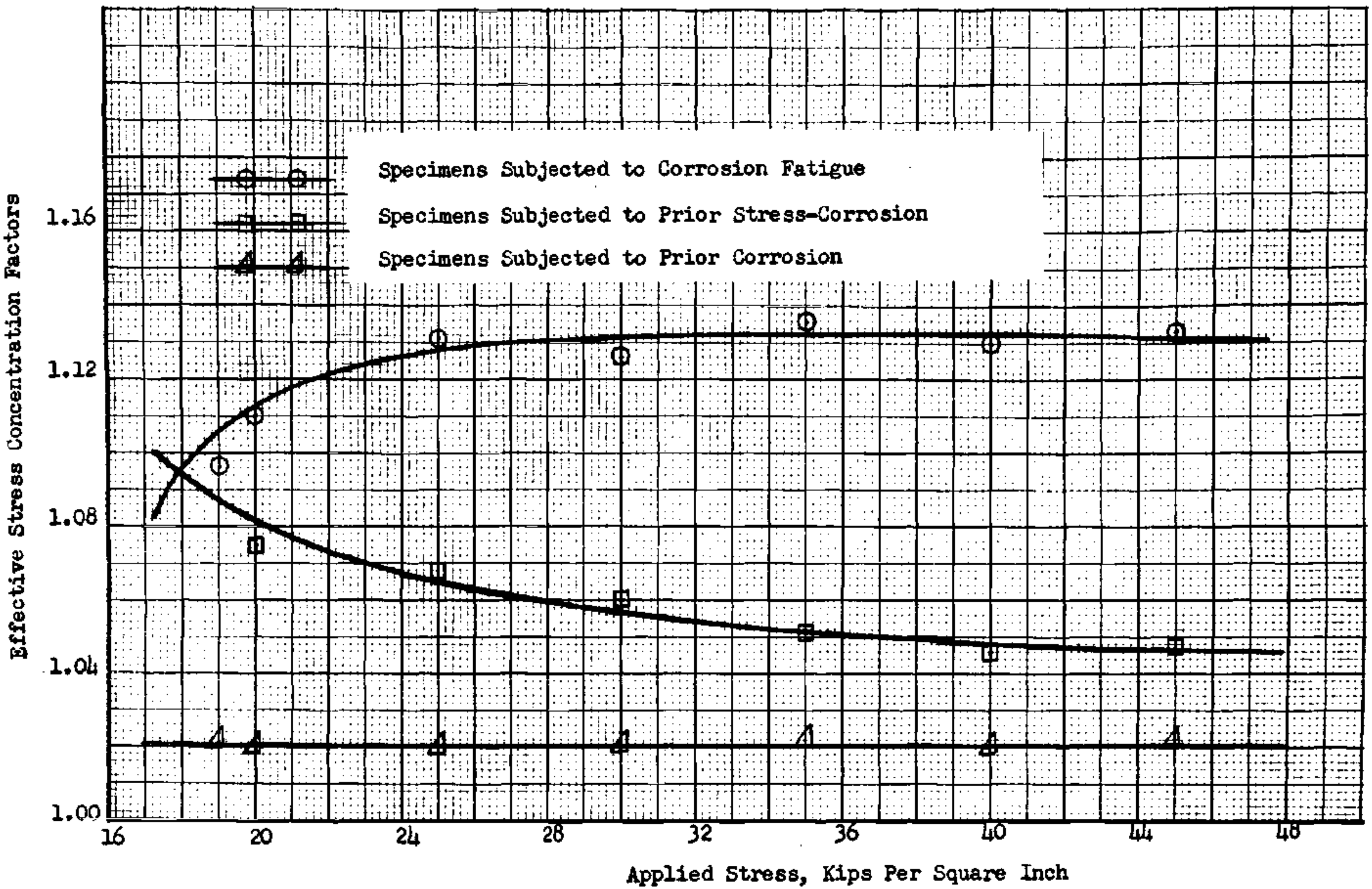

FIGURE 12. COMPARISON OF STRESS CONCENTRATION FACTORS