NACA
CLASSIFICATION CANCELLED

MAR 23 1943

TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 889

EFFECTS OF PRIOR FATIGUE-STRESSING ON THE IMPACT RESISTANCE OF CHROMIUM-MOLYBDENUM AIRCRAFT STEEL

By J. A. Kies and W. L. Holshouser
National Bureau of Standards

CLASSIFIED DOCUMENT

This document contains classified information affecting the National Defense of the United States within the meaning of the Espionage Act, USC 50:31 and 32. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law. Information so classified may be imparted only to persons in the military and naval Services of the United States, appropriate civilian officers and employees of the Federal Government who have a legitimate interest therein, and to United States citizens of known loyalty and discretion who of necessity must be informed thereof.

FILE COPY
To be returned to
the files of the Langley
Memorial Aeronautical
Laboratory.

Washington
March 1943

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 889

EFFECTS OF PRIOR FATIGUE-STRESSING ON THE IMPACT RESISTANCE OF CHROMIUM-MOLYBDENUM AIRCRAFT STEEL

By J. A. Kies and W. L. Holshouser

SUMMARY

Fatigue continues to be an important cause of service failures in highly stressed structural members of aircraft. Fatigue cracks of detectable dimensions usually cannot be found until after a relatively long period during which suitable preparation for such cracks is made by continued stresssing. Once such a crack is started, however, complete failure may be anticipated within a short time, often 10 percent or less of the total service life. Detection of fatigue cracks, even of visible dimensions, is often difficult and is usually practically impossible during operation. There is urgent need for some means of detecting and evaluating the deterioration brought on by fatigue-stressing before cracks appear and of evaluating the damage caused by fatigue cracks after they have reached detectable size.

In attempts to detect and evaluate damage of this kind, the impact behavior of normalized SAE X4130 steel was studied after a variety of repeated stress treatments. Fatigue specimens of several types were used and the effects of surface finish, rest periods, stress amplitude, mean stress, stress concentration, and temperature during repeated stress received consideration. Comparative impact-test results were obtained for several temperatures ranging from room temperature to -78° C.

The results serve to emphasize the seriousness of fatigue cracks, particularly at low temperatures, but are reassuring in the cases in which fatigue cracks are absent or have not developed to a size permitting detection.

I. INTRODUCTION

Practical Importance of Fatigue Failures

A large portion of service failures in load-bearing members of high-speed machines are fatigue failures. This situation, which is especially true of aircraft, seems unavoidable for two general reasons: First, it is far more difficult to determine the strength of a complicated structure under vibratory stresses than under static loading; and, second, it is often difficult or impossible to predict what the dynamic loading conditions will be, particularly during resonance vibrations. The second difficulty is often aggravated by faults in design and a variety of surface conditions difficult to assess, such as inferior machining, corrosion, erosion, and abrasion. Any of these irregularities may result in concentrations of stress for which it is difficult to make ample allowance in the design. Despite these difficulties, the actual number of fatigue failures in aircraft is very small. The increasing dependability of aircraft is attainable only by promptly detecting and replacing damaged parts as well as by maintaining high standards for initial quality of materials, design, and workmanship. An excellent review of the prevention of fatigue failures has been prepared by the staff of Battelle Memorial Institute (reference 1).

A fatigue fracture often occurs suddenly after a long and apparently satisfactory service without visible deformation or deterioration. Once a fatigue crack has progressed to a detectable size, however, it is usually propagated at an ever increasing rate and total failure of the part may be expected within a time that is a small percentage of the service life. Detection of fatigue damage is sure only after a crack has developed, and it is often difficult or even impossible to discover the trouble in time to prevent failure of the member. Although great progress had been made in the technique of crack detection, there is urgent need for a nondestructive method of detecting fatigue damage before a crack starts.

Internal Progressive Changes Due to Failure

It is assumed by many that an obscure progressive change occurs within the metal preceding the formation of a fatigue crack. The often repeated observation that, for a given amplitude of stress in the unsafe range, a fatigue crack appears after a fairly definite number of strain cycles has been imposed and that the higher the amplitude of the strain cycle the smaller the number of cycles required to start the crack for a given material and type of loading may be recalled in support of this assumption.

Many attempts have been made to determine the nature of the differences in the metal before and after it had been fatigue-damaged, short of cracking. These attempts are of two kinds: (1) relatively fundamental studies that include microscopic studies of slip and analyses of X-ray diffraction patterns and (2) empirical studies of the influence of fatigue stress on various mechanical and physical properties, such as hardness, internal friction, impact resistance, magnetic properties, strength under static bending loads, and endurance in a second stage of repeated stressing.

Microstructure and X-ray diffraction patterns.- Much valuable information has been obtained concerning the internal changes that result from fatigue-stressing. Gough (reference 2) showed that, for large single crystals, the fatigue strength of various metals could be expressed in terms of maximum resolved shear stress on the slip planes and that slip on these planes always preceded the opening of a fatigue crack. Other studies of the microstructure of metals before and after fatigue-stressing have shown that slip lines and deformation bands may be developed by both safe and unsafe ranges of fatigue stress, at least in polycrystalline samples of soft iron and probably in some other metals as noted in references 3 and 4 and the discussion by Greninger of reference 5.

The presence of deformation bands in the microstructure of a metallic crystal indicates that the strain in the crystal has not been homogeneous during plastic deformation: that is, in certain regions the deformation took place along combinations of slip planes and slip directions different from the combinations in other regions.

In general, plastic deformation as shown by slip lines resulting from cyclic stress is not in itself an indication of weakness in the material. On the contrary, increases in hardness, tensile strength, and fatigue limit often accompany the development of slip lines. Thus there may be two opposing processes at work during repeated stress: general strengthening by strain hardening and the development of local "sore spots" where cracks may open. If the amplitude of the vibratory stress is below the fatigue limit, the strengthening by strain hardening appears to be predominant, but, if the stress is in the unsafe range, a sore spot often gives rise to a fatigue crack in spite of the general strengthening effects. Metals differ greatly in this respect. The fatigue limit of some metals may be thus raised or lowered by repeated understress or even raised by repeated overstress if the number of cycles is sufficiently limited.

In the study, by X-ray diffraction, of the structural changes that occur during the fatigue of a metal, the desirability of focusing the beam on a sore spot where a crack is expected to open is apparent. If the spot is a great deal smaller in cross section than the X-ray beam, the indications of damage will be greatly restricted and also masked by reflections from relatively undamaged material. This fact may account for the failure of numerous X-ray investigations of fatigue to show decisively a critical difference between fatigue-damaged and -undamaged metal. Although the creation of deformation bands during stressing is not in itself an indication of damage, the fact is well established that any fatigue cracks which may be formed as a result of continued stressing have their origin within regions of slip (reference 2).

A valuable contribution to the knowledge of the nature of internal changes in metal during fatigue stress has been made by Wood and Thorpe (reference 6), whose conclusions covering only annealed brass are summarized as follows: Slip and the primitive yield are suppressed and the yield point is permanently raised by rapid cyclic stressing in equal tension and compression at stresses well above the primitive static yield point. The dispersal of the grains into widely oriented crystallites is inhibited, and internal lattice strains are introduced by rapid cyclic stresses in the unsafe range. No attempt was made to distinguish between the effects of safe and unsafe ranges of stress - that is, stresses below and above the fatigue limit; however, some effects of repeated stress in the unsafe range were clearly shown to be different in kind from the effects of cold work as accomplished by static loading above the primitive yield point. The use of lattice-parameter measurements to detect fatigue damage has been neglected; yet, according to Wood and Thorpe, this feature appears to be more characteristic of fatigue than the usual qualitative estimates of spot diffusion. One difficulty is the low precision with which residual stress can be measured by X-rays.

Despite the extensive studies made, the exact nature of the changes leading to the opening of a fatigue crack is still very obscure and it may well be that the volume of metal involved in the critical changes is so limited in dimensions that available X-ray techniques are not fine enough. It thus appears that studies of microstructure and X-ray diffraction patterns do not immediately offer a means of detecting fatigue damage; a marked refinement in the technique of such studies is necessary.

Engineering and mechanical properties.- Aside from a fundamental approach to the problem, there are a number of possibilities for studying the resultant effects of fatigue by supplemental tests of various physical and mechanical properties. Such studies cannot be expected to reveal what fatigue is, but they are important for the immediate purpose of determining to what extent the various mechanical properties may have been impaired and for the ultimate purpose of forestalling fatigue failure by noting impairments and replacing defective parts.

The situation in regard to the use of supplemental tests is essentially as follows:

Hardness tests offer the advantages of being quick, inexpensive, and frequently nondestructive. The change in hardness resulting from repeated overstress, however, is usually a very small increase which cannot be expressed in terms of damage to the metal. Also, the indenter used in the testing device may not happen to strike a "sore spot" where the damage is greatest and, even if it did, the spot might be too small to affect appreciably the result.

Damping studies have not proved adequate for measuring fatigue damage in service. Such measurements are sensitive to cold work and a number of other factors, all of which tend to obscure any small effects on the damping characteristics that may accompany fatigue damage.

Many studies of internal friction have been reported in the literature. In a few instances the investigators were able to show progressive changes that seemed to follow the course of fatigue in the pre-crack stage. These changes occurred in samples of fairly pure metals carefully annealed at the start. Apparently no one has been able to obtain similar positive indications on other materials. Fewer studies of magnetic property changes have been made, but otherwise the situation is about the same, Magnetic measurements on steel fatigue specimens by Fischer (reference 7) have failed to distinguish between safe and unsafe ranges of stress. Fischer showed that the magnetic changes observed were such as would be caused by partial relief or redistribution of initial residual stresses and that the magnetic changes produced by understressing and by overstressing differed only in magnitude.

The static bending strength of notched specimens fatigue-stressed at low temperatures was used by Davidenkow and Schewandin (reference 8) to detect fatigue damage, and losses in bending strength in the pre-crack stage of fatigue were reported. Their method of crack detection appears to have been insensitive and apparently no attempt has been made to confirm their results.

Endurance in a second stage of fatigue-stressing has been used to establish "damage lines" and curves of equal damage (references 9 to 13). "Second stage" designates a second or supplementary run in a fatigue machine at a suitable stress, usually different from the first. Such tests are time-consuming and are not suitable as a routine method of detecting damage in service parts. The belief that detecting or estimating the degree of damage in the pre-crack stage is possible is, however, given strong support. In a few of the second-stage tests, new fatigue limits were determined following fatigue-stressing as the first stage. In the search for methods of detecting fatigue damage, an important and obvious fact may be overlooked - that a piece of metal damaged in one sense may not be damaged at all in other respects. Specifically, the "damage lines" previously mentioned clearly demonstrate that a metal may be so damaged by cycles of unsafe stress that its subsequent endurance at the same stress is reduced considerably, although the fatigue limit has not been lowered. According to the "damage line" definition of damage by French (reference 9), no damage has been done in spite of the fact that the resistance to a certain value of overstress has been reduced.

Impact testing has been used in attempts to evaluate fatigue damage, the energy required to break a specimen by rapid loading being the quantity measured. This quantity is commonly called impact resistance or impact energy. Oshiba (references 14 and 15), experimenting with annealed carbon steels, reported losses in impact resistance following repeated stresses both below and above the fatigue limit. No attempt was made to detect fatigue damage in high-strength materials, and, although some decreases in impact resistance were associated with the appearance of cracks, the lowered impact values for fatigue specimens in the pre-crack stage actually indicated fatigue damage. The work is inconclusive, however, regarding the utility of this procedure to the study of fatigue in aircraft materials in the pre-crack stage. Kies and Quick (reference 16) found no loss in notched-bar impact resistance of 25S-T aluminum alloy resulting from repeated stresses below or above the fatigue limit. The impact specimens were cut from specimens of uniform circular cross section in the reduced portion that had been fatigue-stressed by axial loading in the Haigh machine. The material throughout the impact specimens had the important advantage of highly uniform stress history; however, the surface layers of the fatigue specimens had been machined away in making the impact specimens and the most severely damaged portions of the fatigue specimens could not therefore influence the impact-test results. Furthermore, the introduction of a machined notch may be expected to have a profound effect on the impact resistance and thereby mask any effect of fatigue.

Experiments by Portevin (reference 17) on notched bars cut from crankshaft steel previously stressed as a rotating cantilever beam could not be expected to yield much information, both because of the introduction of a machined notch and because notched rectangular bars machined from rotating beam fatigue specimens contain material that is decidedly nonuniform as to stress history and do not contain the material nearest the surface where fatigue damage is greatest.

From the foregoing considerations, it seems that in no case has impact testing as a means of evaluating fatigue damage been tried on a high-strength aircraft material under the most favorable conditions.

The fact that aircraft are frequently operated at temperatures of -55° C and occasionally at temperatures of -65° C also has important bearing on the choice of a test procedure for damage detection. Such service conditions are particularly exacting on parts required to withstand shock loading. It is well known that steels, especially ferritic steels in the form of notched bars, generally exhibit very low impact resistance at temperatures below some critical value. The temperature range in which and below which excessive brittleness under impact is to be expected depends on a number of factors, one of which is the severity of any stress raiser such as a notch (reference 18). In the case of unnotched specimens of normalized SAE X4130 steel not subjected to repeated stress, no difference has been found between the impact resistances at room temperatures and at −33° C. This material is widely used for tubular-frame construction in aircraft. The average impact resistance of notched bars of this material – for example, Charpy impact specimens – steadily decreases when the test temperature is progressively lowered from 20° to −78° C (reference 19). Fatigue cracks, because of their extremely sharp roots, may be expected to cause much more drastic embrittlement than the Charpy notch of comparable depth in this temperature interval. It is important, therefore, that the range of testing temperatures include the operating range.

From the foregoing review, impact testing appears a good choice for further study of fatigue damage among the approaches thus far attempted because immediate results of practical interest are obtainable.

II. MATERIAL, TESTING MACHINES, AND SPECIMENS

Heat Treatment and Resulting Tensile Properties

The material consisted of 1/2-inch square bars of SAE X4130 chromium-molybdenum steel of three different heats. The grain sizes and compositions as determined by the manufacturer's analyses of the three heats are given in table I. Banding in varying but usually slight degree was found in the structure of the material as received for all three heats.

Nine batches were normalized separately. The normalizing treatment consisted of holding the steel in lengths of 12 to 18 inches for 60 to 100 minutes at 1600° F (871° C) in a protective atmosphere, removing it from the furnace, and cooling in air to the temperature of the room. The slight scaling of the surface was of no consequence because the specimens were invariably 0.250 inch or smaller in diameter at the test section and all specimens were machined from the centers of the bars. Structural banding was much less in evidence after normalization.

Tensile properties (table II) of each of the nine batches were determined with an Amsler machine and recorded on a Baldwin Southwark autographic recorder.

Notched Krouse Fatigue Specimens – Transverse Impact

Both notched and unnotched fatigue specimens were used. The notched specimens were cylinders 0.250 inch in diameter outside the notch and either $1\frac{3}{4}$ or 2 inches long, depending on which of two Krouse rotating cantilever machines was used. It was ascertained that this difference in length made no significant difference in the measured impact resistance. The encircling notches had sloping sides forming an angle of 45°. The notch roots were of circular contour ground, then polished successively with wet strings impregnated with emery powders, aluminum oxide, and rouge. Different depths of notches and different radii of root contour were used as noted in the tables of results to be discussed.

Transverse impact tests of the notched specimens were made with either a 30-foot-pound Charpy machine or a 7-foot-pound Amsler machine, depending on the range required. Comparisons were restricted to tests made in the same machine. The notched specimens broken in impact at –20° C and at –78° C were cooled in a 1 : 1 mixture of carbon tetrachloride and chloroform to which bits of dry ice were added as required.

Unnotched Moore and Haigh Specimens – Tensile Impact

Smooth (unnotched) specimens of two kinds were used: rotating-beam specimens for the R. R. Moore machine and axial-loading specimens for the Haigh machine; the overall lengths of the specimens were 4 inches and $4\frac{1}{2}$ inches, respectively. Both types of specimen had a minimum diameter of 0.200 inch at the center. Details of the Moore and Haigh specimens are given in references 20 and 21, respectively.

Two surface finishes of slightly different degrees of fineness were used on the smooth (unnotched) fatigue specimens. The finishing operations were carried out as follows: One end of the specimen was held in the collet of a bench lathe and turned slowly by hand while longitudinal strokes with the polishing paper were applied with finger pressure. For the coarser finish designated in this report as aloxite, two polishing papers were used, first 1 G emery made by Norton Company, and then No. 400A Aloxite made by The Carborundum Company. For the finer polish designated 4/0, the previous treatment was followd by similar applications of 2/0, 3/0, and 4/0 emergy papers (Behr-Manning).

Tensile impact tests of the unnotched specimens were made with a Charpy impact machine of 225-foot-pound capacity. Special precautions were taken to minimize bending during the tensile impact; this effect is more pronounced the greater the elongation during impact. Elongation under impact was determined on a 2-inch gage length and is expressed in inches of total extension for the 2-inch length.

In conducting the impact test at low temperature, the tensile impact specimen was cooled to the desired temperature by immersing the tup of the Charpy machine, with specimen and crosspiece attached, in a tank containing a 1 : 1 mixture of water and ethylene glycol to which dry ice was added as needed. The time required to remove the assembly from the bath and to break the specimen was from 3 to 5 seconds. The rise in temperature during this interval was determined by a thermocouple peened into a practice specimen. The temperature at the instant of impact was thus determined to be from -32° to -34° C.

III. EVALUATION OF FATIGUE DAMAGE BY SUPPLEMENTARY TESTS

In order to study the onset of damage and the effects of fatigue cracks on impact resistance, it is necessary to consider the results of many individual tests as well as the results as a whole. For this purpose a variety of specimen shapes, fatigue machines, and test conditions were used.

EFFECTS OF REPEATED STRESSING AT ROOM TEMPERATURE

Specimens Stressed below the Fatigue Limit

Experiments were performed to determine whether cyclic stressing below the fatigue limit is detrimental to impact resistance. Several types of specimen were used under a variety of conditions as follows:

Notched specimens stressed as rotating cantilever beams in a Krouse machine were tested under a variety of conditions (table III). No loss in impact resistance was detected regardless of the different notches, testing temperatures, or stress treatments. No cracks were found before or after the impact test. Examination were made with a hand lens and a binocular microscope.

Smooth (unnotched) specimens were subjected to about 20,000,000 stress cycles in the fatigue limit range (R. R. Moore machine) and then broken in tensile impact either at room temperature or at -33° C (table IV). No decrease in impact resistance or elongation was found at either temperature and there was no evidence of cracks before or after the impact tests. Examinations by use of a binocular microscope were made both with and without a wet magnaflux treatment of the specimen.

Specimens that had been stressed by axial loading in a Haigh machine below the fatigue limit were broken in tensile impact. Table V shows the stress treatments and the results. No significant losses in impact resistance were noted.

Specimens Stressed above the Fatigue Limit

Notched fatigue specimens broken in transverse impact at room temperature, at -20° C and at -78° C.- There are a few advantages in the use of notched specimens which apply mainly to the study of the effects of overstressing. These advantages are as follows: The notch simulates conditions of stress concentration often found in service parts. The position of the fatigue crack is restricted, which makes crack detection less time-consuming. Impact tests at a number of low temperatures can be made relatively easily. A disadvantage is that the permanent deformation due to impact cannot be measured accurately.

A group of 100 notched specimens (batch 4) with a notch 0.040 inch deep and a root radius of 0.01 inch was used. A few specimens were broken in impact in the unstressed condition, but the majority were first fatigue-stressed as rotating cantilever beams in a Krouse machine for various numbers of cycles of the same nominal stress, ±40,000 pounds per square inch, based on the diameter at the root of the notch with no allowance for stress concentration.

Twelve of the notched specimens were allowed to fail in the fatigue machines. Their endurances were fairly evenly scattered from 310,000 cycles to 10,000,000 cycles.

The average impact resistances determined for specimens at various stages of fatigue are plotted against the temperature of impact test in figure 1. The average impact resistances after 400,000, 500,000, and 600,000 cycles were weighted to allow for the specimens that had zero impact resistance as a result of fatigue failures. (See appendix A.) Comparisons of the average impact resistances before and after stressing are given in table VI. The table shows greater percentage losses at low temperatures than at room temperature for the specimens run 200,000 cycles or more.

The notched specimens of batches 1 and 2 previously tested (tables VII and VIII) were not studied in such detail as the notched specimens of batch 4. All the results are, however, in good agreement insofar as the completeness of the data permits the following conclusions to be drawn:

1. Fatigue damage as shown by a lowered impact resistance began in the same range of stress cycles whether measured at room temperature, at -20° C, or at -78° C.

2. The onset of lowered impact resistance was accompanied by the appearance of surface cracks. Low impact values were very rarely found without detectable cracks.

3. Fatigue cracks were far more detrimental in impact tests at low temperatures than at room temperature.

Studies of average values of impact-test results of fatigue-stressed notched specimens were of little use unless correlated with the examination and results of the individual specimens. The variation in behavior of individual specimens was very marked and the fact that specimens had received a certain number of cycles of stress above the fatigue limit was of slight importance in comparison with the question of whether cracks had started. Some notes on individual specimens are given in appendix B.

<u>Unnotched fatigue specimens broken in tensile impact at room temperature and at -33° C.</u>- There are certain advantages in the use of unnotched specimens in studying the onset of fatigue damage and the influence of cracks on the impact resistance of steel. These advantages, which apply

mainly to the study of the effects of overstressing are as follows: Better control of diameter of the specimen and its surface finish is possible during machining and a larger volume of metal with a greater area of the surface layer is stressed at or very near the maximum fiber stress. The detection of damage in individual fatigue specimens is more certain since the scatter in the results of tensile impact tests of unnotched specimens is slight in comparison with the results of transverse impact tests of notched specimens. The permanent elongation of the specimens under tensile impact can be measured with satisfactory precision in most cases. The interpretation of the tensile impact results for damaged specimens, especially at lower temperatures, is simplified because of the narrowness of the scatter as compared with machine-notched specimens.

Two different surface finishes were used in most of the experiments with smooth (unnotched) specimens stressed above the fatigue limit because of the generally recognized importance of this variable in the formation of fatigue cracks. The two surface finishes used were described in detail in a preceding section.

The Moore specimens were all stressed at ±80,000 pounds per square inch in the R. R. Moore machine. The fatigue limit of the material was ±59,000 to ±62,000 pounds per square inch. Supplementary tensile impact tests were made at room temperature and at -33° C. The impact energy and the elongation are given in figures 2 and 3, respectively; the results obtained with the 4/0 and aloxite surface finishes are shown separately. All specimens showing impact resistance less than 47 foot-pounds (fig. 2.) were found to contain unmistakable surface cracks after the impact test. No specimen showed more than two cracks, and one specimen, which showed an impact energy of 48.1 foot-pounds at -33° C, had a visible crack. All specimens showing less than 0.130-inch elongation (fig. 3) had visible cracks. This effect was also true of the specimen having an impact resistance of 48.1 foot-pounds after 75,000 cycles of fatigue stress not shown as damaged in figure 2.

All the specimens were examined with and without the wet magnaflux treatment, under a magnification as high as 100 diameters, immediately after the repeated stress treatment and again after the tensile impact test.

The following summarizing statements are supported by the results shown in figures 2 and 3:

1. No significant differences in the endurance limit, the impact energy, or the elongation during impact could be attributed to the two different polishes used on specimens tested in fatigue by transverse loading in the R. R. Moore machine.

2. Two was the maximum number of fatigue cracks found on any specimen regardless of the surface finish.

3. No difference was detected between the tensile impact resistance at −33° C and at room temperature for the steel in the pre-crack stage of fatigue.

4. The average elongation of the steel in the pre-crack stage of fatigue during impact was slightly less at −33° C than at room temperature.

5. Damage of steel fatigue-stressed for about the same number of cycles was detected equally well by impact tests at room temperature and at −33° C.

6. The detection of fatigue damage by measurement of impact resistance or of elongation was not achieved until after cracks had been developed in the material.

Supplementary tensile impact tests of axial-loading fatigue specimens were made in a Haigh machine with variable ratios of tension to compression. The results are grouped in order of increasing mean tensile stress. In these experiments, the tensile stresses during fatigue were in some cases sufficient to cause appreciable permanent sets. The maximum total extension was 0.075 inch.

In order to interpret these results, it is necessary to known the relationship between extension during repeated stressing and the results of the impact tests – that is, impact energy and elongation.

Extensions during fatigue were accordingly measured for a number of specimens of batch 9 and these measurements were plotted against tensile impact energy and elongation during impact. No cracks were found either before or after the impact test. Examinations were made with a hand lens and a binocular microscope. The results are shown in figure 4. All impact fractures were ductile and maximum losses in elongation and impact resistance were considered small.

In general, the greater the previous extension the greater were the losses in elongation and impact energy. The scatter was less obscuring in the case of elongation than in the case of impact energy.

A number of specimens (batch 9) were fatigue-stressed in equal tension and compression (mean stress = 0) by axial loading with the stress amplitudes ranging from ±48,000 to ±52,000 pounds per square inch. Aloxite finish was used on all the specimens of this group. Examinations with a binocular microscope were made after repeated stressing and again after the tensile impact tests. The maximum number of cracks found in any one specimen was four. Impact tests were made at room temperature and at -33° C. The impact-test results and a report of the inspections are given in table IX. The following statements summarize the findings:

1. There was no loss in impact resistance unless surface cracks were opened up by the tensile impact test. Such cracks could not always be detected in advance of the impact test.

2. In general, there was no loss in elongation without the simultaneous appearance of cracks. A relatively unimportant exception was found in specimen HI 34c.

3. Five of the specimens, which showed only minute surface cracks after the tensile impact tests, showed no losses in impact resistance or elongation. This situation was unusual since, in all other groups of tests, fatigue cracks were always accompanied by losses in impact energy, and where elongations were measured losses were likewise detected.

A group of Haigh specimens of batch 1 were subjected to repeated axial stressing in the range from -28,800 to +63,600 pounds per square inch at a mean tensile stress of 17,400 pounds per square inch. Aloxite and 4/0 finishes were used. Some of the specimens were removed from the fatigue machine before fatigue cracks appeared and some after cracks were noticed. Inspection for cracks was made with a binocular microscope following the impact tests.

The results of the tensile impact tests at room temperature are shown in figure 5. Although the number of specimens was not large, the following indications seem clear:

1. There was no loss in impact resistance except for specimens containing fatigue cracks.

2. The damage as shown by lowered impact resistance was postponed by the finer 4/0 polish.

3. All the specimens containing cracks had the aloxite polish. The cracks were numerous, there being more than 100 in one specimen. The coarser polish evidently contributed to the formation of numerous surface cracks in this set of specimens. This result is in contrast to the previous findings of very few cracks in Haigh specimens and Moore specimens at zero mean stress. It is thus indicated that the mean tensile stress and the coarser polish together were responsible for the large number of surface cracks found in the present set of specimens.

4. Four crack-free specimens not represented in figure 5 were broken at −33° C. These specimens showed the same impact resistance as crack-free specimens broken at room temperature.

Twenty-two Haigh specimens (batch 3) were subjected to repeated stress at a mean tensile stress of 31,000 pounds per square inch in the range from −15,200 to ~~77~~,300 pounds per square inch. One specimen had the coarser aloxite finish and the rest had the 4/0 finish. After they were stressed for various numbers of cycles and then broken in tensile impact, 10 specimens having the finer polish were found to contain surface cracks when examined with a binocular microscope. Of these specimens, five had been broken at room temperature and five at −33° C. The maximum number of cracks found in any one specimen was five, and two cracks was the usual number.

On the other hand, the one specimen HI 49 with the coarser polish developed at least 25 surface cracks. Another similar specimen HI 6B from a different batch (batch 9), run at the same stress, developed several hundred surface cracks after 17,000 cycles.

It is therefore again evident that with the aloxite polish many more surface cracks formed than with the finer 4/0 polish. No loss in impact resistance occurred except in the specimens that developed surface cracks.

A group of Haigh specimens (batch 9) was subjected to repeated stress at a mean tensile stress of 50,000 pounds per square inch in the range from 10,500 to 89,500 pounds per square inch. Aloxite and 4/0 finishes were used. The specimens were removed after various numbers of stress cycles and the permanent extensions acquired in the fatigue machine were measured. The surfaces were examined for cracks with the aid of a binocular microscope. Tensile impact tests were then made at room temperature and at −33° C and the specimens were reexamined. The impact-test data are shown in figures 6 to 9. The following deductions were made from a study of the results of these tests:

1. Small plastic extensions (up to 0.025 in. total) were acquired during the first few thousand cycles of stress. During this period, the stretch was gradual as was proved by the fact that the head of the Haigh machine had to be raised slowly to keep the air gaps equalized in the magnetic driving mechanism of the machine. After the first few thousand cycles, no further adjustment of the head was necessary and measurements of the specimens showed that specimens run many thousand cycles had streched no more than specimens run a few thousand cycles.

2. Small losses in elongation (during tensile impacts) resulted from the first few thousand cycles of stress (figs. 6 and 7) in which plastic extension had occurred. After this adjustment period there was no further change in elongation until after fatigue cracks had developed. It should be recalled that, in the case of Moore specimens (fig. 3), no permanent sets were imposed during fatigue and no losses in elongation occurred as a result of the first few thousand cycles of stress. This behavior was interpreted as showing that the initial small losses in elongation for the Haigh specimens were due to cold work and that measurements of elongation in tensile impact were incapable of detecting any further progressive changes due to fatigue until after cracks were started. Cracks were found on all specimens that showed less than 0.120-inch total extension in the tensile impact tests.

3. Losses in elongation could be detected no earlier at −33° C than at room temperature.

4. As in the case of the Moore specimens (fig. 3), elongations were slightly less at −33° C than at room temperature.

5. No losses in impact energy (figs. 8 and 9) were evident until after fatigue cracks were started. The failure of these results to show an early change due to cold work such as found by elongation measurements was attributed to the magnitude of the scatter. This effect was suggested by the results of figure 4.

6. Cracks were found on all specimens having an impact resistance less than 47 foot-pounds (figs. 8 and 9). No difference was detected in the tensile impact resistance at −33° C and at room temperature for specimens not containing visible cracks. It follows that the impact tests at −33° C and the impact tests at room temperature were about equally sensitive in indicating the beginning of cracks.

7. As shown in figures 6 to 9, a few individual specimens having the 4/0 polish endured several times as many cycles of stress without loss in elongation or impact resistance as the specimens with the aloxite finish which were run to failure. This result was contrary to the case of the Moore specimens (figs. 2 and 3). In that case the finer polish was no better. The difference was attributed to the detrimental effect of combining small plastic extensions with the coarser finish.

8. On the specimens given the finer 4/0 polish, the maximum number of surface cracks was three. On the other hand, the specimens given the aloxite polish developed many cracks, the maximum for one specimen being in excess of 25. This situation was similar to that found in previously discussed groups of Haigh specimens subjected to mean tensile stresses of 17,400 pounds per square inch or more.

Tests were made at a mean tensile stress of 77,000 pounds per square inch to check the preceding conclusions and to extend further the study of the relationships between mean tensile stresses and the formation of surface cracks. Aloxite and 4/0 surface finishes were used. The range of stress applied was from 27,000 to 127,000 pounds per square inch. The specimens were removed from the fatigue machine after various numbers of cycles of stress and then broken in tensile impact at room temperature and at −33° C. Impact energies and elongations during the tensile impacts were measured. Examinations were made with a binocular microscope before and after the impact tests. Many of the cracks were not found until after the specimens were pulled open in the impact tests.

The impact energies and elongations are plotted as functions of the numbers of prior stress cycles in figures 10 to 13. Figure 14 shows the relationship between impact energy and elongation. The outstanding points as indicated by the data are as follows:

1. The losses in elongation (figs. 10 and 11) due to the first few thousand cycles of stress were about the same as noted previously for a mean stress of 50,000 pounds per square inch. There was no further change in elongation until after cracks could be detected. Regardless of the temperature at which the impact tests were made, cracks were found in all specimens showing less than 0.125-inch extension during impact or at impact resistances less than 47 foot-pounds (figs. 12 and 13). It is therefore again evident that measurements of elongation and tensile impact resistance are incapable of detecting progressive changes due to fatigue until after cracks are started.

2. Damage was detected no sooner by impact tests at −33° C than by tests at room temperature.

3. The elongation in tensile impact was slightly less at −33° C than at room temperature. This effect is easily seen in figure 14, which gives the relationship between impact energy and elongation for this group of specimens. The scatter in elongation was least for uncracked specimens (high impact resistance) and for specimens having very large cracks (low impact resistance). The scatter in elongation was large for specimens having intermediate impact resistances. This result was due to the erratic form of the fracture surfaces and to the difficulty in fitting together the pieces of some of the fractured specimens. The over-all limits of precision in measurements of elongations were in most cases ±0.005 inch and never more than ±0.010 inch.

4. The high mean tensile stress facilitated the production of numerous surface cracks for both surface finishes. The surfaces became so roughened by strain markings during repeated stress that the two initial surface finishes were usually indistinguishable at and near the centers of the specimens, even though necking was not apparent.

5. In figures 10 to 13, it is apparent that some individual specimens with the finer 4/0 polish endured more cycles of stress than any of the specimens with the aloxite

finish which were run to failure. This capacity to endure more cycles of stress was evidently not possessed by all specimens of this group with the finer polish. This fact may be explained by occasional imperfections in the finer polish.

6. Thus far it has appeared that measurements of impact resistance and elongation are not satisfactory indicators of fatigue damage in the pre-crack stage.

Relationship between Crack Size and Impact Resistance

Removal of Cracks

As pointed out in the introduction, shock loading may be a common occurance in the service life of aircraft, particularly military aircraft. Notches are danger spots under such conditions and, because fatigue cracks are probably the sharpest kind of notches encountered in service, it is important to know the effects of notch size on impact resistance. From a more academic standpoint the following experiments may be considered as further investigations to determine the limits of sensitivity of impact tests in detecting fatigue damage.

Study was made of specimens of batches 3, 6 and 9, which had been fatigue-stressed by axial loading until cracks were formed. The specimens were all the same size (0.200-in. minimum diameter) and initially had the same characteristics under tensile impact. Although it is to be expected that notched specimens of different batches may reflect very small differences in heat treatment, it was found that the results of the tensile impact tests of the specimens of the three batches were hardly distinguishable. Average values for impact energy and elongation were plotted against average sizes of cracks. The averages were restricted to groups of individual test results falling within suitable intervals of crack size in order to distribute the statistical weights as evenly as practicable. Each individual test result entered into only one average. Separation of groups was made according to crack size only. Unequal class intervals were used. Separate analysis with equal class intervals gave the same results but are not included here.

The crack dimensions (length and maximum depth) were measured by a traveling microscope focused on the fracture of the specimen. Most of the fractures studied showed only one detectable fatigue crack entering directly into the fracture produced by impact. In the few impact fractures showing two fatigue cracks, the dimensions of only the larger crack were used since its size seemed to be the controlling factor.

The variation of average impact energy with average maximum crack depth in tests conducted at −33° C and at room temperature is shown in figure 15. Values shown for specimens having zero crack depth were taken from tests of specimens not stressed in fatigue. There was no perceptible difference in the results at −33° C and at room temperatures for specimens showing the smaller cracks. For cracks more than 0.65 millimeter deep, that is, for penetration of over 13 percent of the minimum diameter of the specimen, the average impact resistance at −33° C was less than half the value at room temperature. This critical depth of crack at which the temperature effect became important corresponded to the steepest part of the combined curve (fig. 15).

The existence of a critical crack size at which the temperature effect begins to show itself was more clearly demonstrated when the crack length was also taken into account. Actually, the chord defined by the ends of the crack was measured and, for the largest crack measured, the crack length measured along the surface exceeded the chord by only $5\frac{1}{2}$ percent. At the critical size beyond which the behavior at −33° C differed from that at room temperature, the arc exceeded the chord by only 0.7 percent. These discrepancies are so much smaller than the range of scatter in the results of the impact tests that the term "crack length" will be used instead of "chord" in this report.

Figure 16 shows the variation in average impact energy with average values for the product of the crack depth by the length dl, which is approximately proportional to the area of the face of the crack. For values of this product exceeding 0.70 square millimeter, the loss in impact resistance was more serious at −33° C than at room temperature. This critical size corresponds to the steepest portion of the curve, with the exception of the initial drop. The average elongation during impact (fig. 17) also decreased rapidly as the product dl reached the value corresponding to the divergence of behavior for the two temperatures used. The point of divergence corresponds to crack areas about 3 percent of the minimum cross section of the specimen.

The question remains whether, in aircraft structures of normalized SAE X4130 steel that have been subjected to vibratory stresses, low impact resistance will be encountered at low temperatures. A partial qualitative answer may be deduced from the foregoing data; no adverse low-temperature effect seems probable unless excessively severe notches or equivalent constraints to plastic flow are embodied in the design or unless fatigue cracks of detectable size develop. The data on unnotched fatigue specimens show that repeated stresses above or below the fatigue limit do not produce significant degrees of embrittlement at temperatures as low as -33° C, unless excessive permanent deformation results or until detectable fatigue cracks are produced. In a preceding section on notched rotating cantilever specimens, it was shown that no significant embrittlement at -20° C or at -78° C resulted from repeated stressing at room temperature unless detectable cracks were formed. As shown in figures 15 to 17, very small fatigue cracks in unnotched specimens do make a considerable difference in the tensile impact resistance and in the elongation under impact. It appears logical to assume that the lower the temperature the smaller will be the critical size of cracks which produce an adverse low-temperature effect on impact energy and elongation. This point has not been investigated, however.

Additional experiments were made to determine whether the occurrence of fatigue cracks is accompanied by detrimental changes throughout the rest of the metal subjected to the same stress treatment as the metal in the immediate vicinity of the cracks. It has been shown thus far that impact tests are incapable of detecting fatigue damage unless cracks have started. Although small losses in impact energy and elongation were shown to accompany small plastic extensions acquired during fatigue (fig. 4), this effect was identified as a result of the plastic deformation and not of repetitions of stress.

It is ~~to be~~ expected, therefore, that fatigue specimens from which fatigue cracks have been removed will show small losses in elongation and impact resistance, provided plastic extensions have been imposed. Although it was anticipated from reference 16 and from forgoing results that no additional effect would be found in the remaining metal after crack removal, it remained to be shown experimentally for normalized SAE X4130 steel whether such was the case.

Since it is required that the remaining metal have a stress history the same as that of the removed metal, the condition is best fulfilled by using specimens that have been stressed in axial loading. Tensile impact tests were accordingly made of such specimens, from which surface layers containing fatigue cracks were machined away. Comparison impact tests were made on unstressed specimens and on specimens stretched during fatigue without developing fatigue cracks.

Owing to the limited load capacity of the Haigh machine it was not convenient to administer repeated stress as equal tension and compression. Specimens about 0.170 inch in diameter would have been required, and they would have been too small for satisfactory use after they were machined to remove visible cracks.

Specimens having 0.200-inch minimum diameter were stressed by axial loading, as shown in table X. As soon as necking occurred or cracks were detected the specimens were removed, machined down, and polished to minimum diamters of 0.170 inch or to 0.150 inch as shown in the table, after which they were tested under tensile impact.

The condition of the surfaces of two specimens after removal from the fatigue machine is illustrated by figure 18(a). Besides unmistakable fatigue cracks, the surfaces contain strain markings that were not visible before the repeated stress treatment. Figure 18(b) shows the appearance of the surfaces of these specimens after the fatigue cracks had been removed by machining and the surface had been repolished in preparation for the impact tests.

All specimens were subjected to mean tensile stresses sufficient to cause some permanent extension. In two cases, HI 13a and HI 19a, slight necking occurred but without detectable cracking. After being machined down to 0.150-inch minimum diameter, these specimens showed lower impact resistance than a companion specimen, HI 63, from which cracks had been removed by machining. This result indicates that the slight differences previously noted can be attributed to cold working, independently of the occurrence of cracks in the outer, removed layers.

The last four specimens given in table X showed minute surface cracks opened up by tensile impact, of which only one was detected prior to the impact test. In the absence of knowledge to the contrary, it can be assumed that failure to detect cracks may be attributed to an insufficiently sensitive method. Differences in the impact resistance of 14 percent or less below the average value for specimens not stressed in fatigue were obtained. According to the results of specimens HI 13a and HI 19a, some of this difference may have been due to the cold-worked condition of the metal.

The results show that the impact resistance was slightly lower for fatigue-stressed specimens which had been machined to remove fatigue cracks than for specimens not subjected to repeated stress. The difference, if real, is considered too small to be of engineering importance.

Effect of Intermittent Rest Periods during Fatigue-Stressing

A theory of fatigue proposed by Orowan (reference 22) might indicate that intermittent rest periods during fatigue-stressing would have a beneficial effect on the endurance of a metal. It would be necessary, however, for the temperature to be sufficiently high during resting to produce a stress anneal without simultaneously softening the material enough to lower its fatigue strength. Gough and Wood (reference 23) stated that, in their experience, the endurance of fatigue specimens is always increased by rest periods. Daeves, Gerold, and Schulz (reference 24) reported that increases in excess of 200 percent for the average endurances of two carbon steels were obtained by immersing rotating-beam fatigue specimens in oil at 140° C during the rest periods. They also reported that a 7-percent increase in average endurance resulted from resting at room temperature. Schulz and Püngel (reference 25) found that the endurance of a carbon steel subjected to repeated impact might be increased or decreased depending on the schedule of rest periods at room temperature. On the other hand, Bollenrath (reference 26) found that at room temperature no benefit accrued from resting of overstressed specimens of a chromium-molybdenum steel. Bollenraths's data are very complete. He could not, of course, investigate all possible variables. From a practical consideration, the length of the rest periods could stand investigation for the empirical reason that such periods commonly vary a great deal in service and for the theoretical reason that conditions postulated by Orowan might, if given enough time, be relieved by rest periods.

In view of the apparent uncertainty concerning the necessary condition for the beneficial effect of intermittent rest periods, the following experiment was undertaken: Sixty-four specimens (batch 5) were fatigue-stressed as transversely loaded rotating beams in the R. R. Moore machine. Some specimens were run continuously and others were run and rested intermittently at stresses above and in the fatigue limit range as described in table XI. The range of stress in which both failure and endurance past one million cycles without failure were obtained in continuous runs extended from a maximum fiber stress of ±60,000 to ±63,000 pounds per square inch. It may be noted particularly that, at ±64,000 pounds per square inch, the range of endurance and the average endurance were nearly alike for continuous runs and for those interrupted by rest periods. Of the various schedules of rest periods tried, none seemed to possess any marked advantage.

Within the range between ±60,000 and ±63,000 pounds per square inch, the interpretation of the results is less sure than before. For practical purposes, however, no general improvement was noticeable and, even if it existed, the amount was too small for practical significance. It is obviously impossible to say that in individual cases no improvement was produced. The only possible way of measuring general improvement, however, is on a statistical basis and, on this basis, it must be concluded that no significant improvement resulted from rest periods at room temperature. Nor did resting at 60° C and 100° C in the individual cases used produce improvement of useful magnitude.

EFFECTS OF FATIGUE-STRESSING AT -40° C

Specimens of the form shown in figure 19 were machined from batch 8 and were given repeated stress treatmenst in a Baby Rayflex flexural fatigue machine. The specimen was designed to avoid indeterminate stresses resulting from clamping and also to have a specimen suitable for subsequent transverse-impact testing. A special loading arm was also designed and tuned to the proper frequency in the machine. The moving assembly consisting of flexible support, clamp, armature, specimen, and loading arm is shown in figure 20.

The distribution of inertia loading, corresponding bending moments, elastic deflection, and stresses were solved graphically using Stodola's method (reference 27) of successive approximations. This solution is for free vibrations and the disturbing influences of the automatic cut-off contact mechanism and bumpers were neglected.

The form of the deflection curve and the corresponding bending moments for 60 cycles per second are plotted for an arbitrary case in figure 21. The distribution of the alternating component of the stress in the reduced portion of the test specimen is included in figure 19. For all stress amplitudes within the capacity of the machine, the bending moments and the deflections differ from the case of figure 21 only in the matter of scale. Both scales would be altered by the same factor. No correction was necessary for differences in elastic modulus at −40° C and at room temperature, since these changes were previously found by Rosenberg (reference 19) to be very slight. No change in tuning of the assembly was necessary for operation at −40° C. A steady maximum bending stress of 1200 pounds per square inch is imposed by the forces of gravity.

In order to operate the machine at a low temperature, the control mechanism was detached and placed outside an especially constructed refrigerator in which the rest of the machine was placed. The upper compartment of the refrigerator was of ample size and was kept well filled with dry ice. This compartment could be opened for the addition of dry ice without disturbing the temperature of the compartment below containing the fatigue-testing device. The walls were insulated with a 3-inch lining of rock wool and the seams of the steel casing were sealed airtight to prevent condensation within the insulation. All condensation within the cold box took place on or very near the dry ice. No condensation formed on the fatigue machine except when the machine was removed from the box. The conditions were such that the temperature within the lower chamber was maintained overnight between −40° and −45° C without any servicing.

The fatigue limits at room temperature and at −40° C were determined for specimens cleaned by washing in carbon tetrachloride. Check determinations of the fatigue limit were also made on lanolin-coated specimens, but no significant difference was detected. The scatter in the results was such that effects of less than ±2000 pounds per square inch were obscured. The fatigue strengths determined at room temperature and in the interval from −40° to −45° C are given in figure 22; the nominal values found at the two temperatures are, respectively, ±51,000 and ±63,500 pounds per square inch superimposed on a steady bending load of 1200 pounds per square inch. Fatigue limits at room temperature obtained for transversely loaded rotating-beam specimens in the R. R. Moore machine were from ±59,000 to ±61,000 pounds per square inch, a value that indicates a factor of about 1.17 for the corner effect.

The impact results will be considered in two classes: those for specimens without detectable fatigue cracks and those for specimens with cracks detected by the aid of the wet magnaflux treatment.

Specimens without Fatigue Cracks

Impact results on unstressed specimens were taken as the criterions by which damage was estimated. The treatments of the specimens and the impact results are presented in table XII. A distinction between fibrous (tough) and granular (brittle) fractures is made in table XII. Photographs showing such distinctions have been published by Rosenberg (reference 19). A study of the data suggests the following three cases in which slight damage possibly is indicated:

1. Specimens overstressed for 30 percent of the expected life at room temperature and broken in impact at −78° C were slightly lower in average impact energy and in average fibrous or tough portion of the fracture than the unstressed specimens broken in impact at −78° C.

2. The same was true of specimens overstressed for 30 percent of the expected life at −40° to −45° C and broken at −78° C.

3. Specimens stressed in excess of 10 million cycles at the fatigue limit at −40° to −45° C and then broken under impact at room temperature showed very slight lowering of the average impact energy and average fibrous portion of the fractures.

In no case was the deficiency large enough to discount the possibility that it might be due to chance scatter.

In general, it may be concluded from the data of table XII that prolonged stressing at the fatigue limit either at room temperature or in the interval from −40° to −45° C is not seriously detrimental to impact resistance and that overstressing for 30 to 35 percent of the expected endurance under the same temperature conditions, without the formation of detectable cracks, is not seriously detrimental to impact resistance.

Specimens with Fatigue Cracks

There was no distinction detected between fatigue cracks produced at −40° C and at room temperature. All specimens fatigued by flexure sufficiently to form cracks showed fractures entirely crystalline (brittle) when broken under transverse impact at −78° C, provided one or more cracks were on the tension side during impact. The resistance to impact was very low at room temperature and at −78° C (table XII). It may be noted from the table that three specimens having fatigue cracks occupying almost half the cross section of the specimen still retained about half the original impact resistance at −78° C, when the cracks were confined to the compression side during impact. This fact suggests that the material had not degenerated in uncracked portions and that the notch effect of the crack was small in compression.

IV. CONCLUSIONS

As a possible means of detecting and evaluating fatigue-damage in steel the impact resistance was determined by supplementary tests of specimens that had been fatigue-stressed short of failure. The impact behavior of normalized SAE X4130 steel was studied following fatigue-stressing under a variety of conditions of stress amplitude, mean stress, stress concentration, stress distribution, and temperatures during stressing. Comparative data were secured for a variety of impact testing temperatures ranging from room temperatures to −78° C. The following results were obtained:

1. No loss in impact resistance resulted from repeated stressing below the fatigue limit. This fact was established for the notched Krouse specimens and for the unnotched Moore and Haigh specimens.

2. For the notched specimens stressed above the fatigue limit, all losses in impact resistance were accom-

panied by fatigue cracks at the roots of the notches.

3. Fatigue damage in the notched specimens was detected equally early by impact tests at room temperature, at -20° C, and at -78° C.

4. For the notched specimens it was shown (appendix B) that, for a given percentage loss of initial impact energy, a much deeper crack can be tolerated at room temperature than at -20° C or at -78° C, but the low temperature effect was not appreciably greater for cracked than for uncracked specimens until the cracks had become visible when viewed at a magnification of 8.

5. The fact that notched rotating cantilever fatigue specimens had received a given number of cycles of a given overstress was of small importance compared with the question of whether fatigue cracks had started.

6. Tensile impact tests of unnotched specimens stressed as rotating beams and axially loaded specimens stressed in equal tension and compression gave no indication of any loss in elongation or impact energy until surface fatigue cracks were present. These cracks were not always found in advance of the impact test. Damage was detected no sooner at -33° C than at room temperature.

7. For the specimens referred to in conclusion 6, there was no difference between the impact energy at -53° C and at room temperature during the pre-crack stage; however, the elongation was slightly less at the lower temperature.

8. Axially loaded specimens subjected to repeated overstress superimposed on mean tensile stresses varying from 17,400 to 77,000 pounds per square inch extended plastically during the first few thousand cycles of stress, after which no further extension took place during the pre-crack stage of fatigue. Small losses in elongation and tensile impact energy accompanied this initial extension, but these losses were also restricted to the first few thousand cycles of stress. No further change in elongation or impact energy took place until the advent of fatigue cracks.

9. Two different surface finishes, aloxite and 4/0, made no difference in the fatigue or impact results obtained on unnotched Moore specimens. For Haigh specimens, however, for which mean tensile stresses during fatigue

ranged from 17,400 to 77,000 pounds per square inch, the endurance at a given overstress was somewhat higher for the specimens having the finer 4/0 polish.

10. Moore and Haigh specimens, for which the mean tensile stress during fatigue was zero, developed five cracks at the most in any single specimen regardless of the finish used.

11. Haigh specimens given the aloxite polish and then subjected to mean tensile stresses of 17,400, 31,000, and 50,000 pounds per square inch during fatigue developed numerous (maximum about 100) fatigue cracks if allowed to run to failure or near failure. Specimens given the 4/0 finish and stressed under these conditions developed a maximum of from two to five cracks.

12. Haigh specimens subjected to a mean tensile stress of 77,000 pounds per square inch developed large numbers of fatigue cracks (maximum about 200) regardless of the finish used.

13. It was evident that with the coarser polish large numbers of cracks formed only where some plastic deformation occurred during fatigue. If the mean tensile stress was sufficiently high (77,000 lb/sq in.) this difference was either nonexistent or masked by the effects of plastic deformation.

14. Axially loaded fatigue specimens that had developed fatigue cracks were used to study the relationship between crack dimensions and tensile impact behavior. Even the smallest cracks measured (0.05 mm maximum depth) produced losses in impact energy and elongation.

15. The average impact energies of cracked specimens were the same at room temperature and at −33° C for cracks less than a certain critical size. For cracks larger than the critical size the average impact energies were less at −33° C than at room temperature.

16. Specimens fatigue-stressed by axial loading sufficiently to produce fatigue cracks were machined to remove the surface layer containing the cracks. The tensile impact resistances of the remaining specimens were slightly less than for comparable specimens not fatigue-stressed. This loss was attributed mainly or wholly to the plastic extension received during repeated stress.

17. Specimens fatigue-stressed by flexure in the temperature interval, −40° to −45° C, showed no evidence of lowered impact resistance at either room or low temperatures, provided no detectable cracks were formed.

18. The ratio of the fatigue limits of specimens of normalized SAE X4130 steel stressed by repeated flexure at −40° to −45° C and at room temperatures was 1.24.

National Bureau of Standards,
Washington, D. C., November 25, 1942.

APPENDIX A

METHOD OF OBTAINING CORRECTED AVERAGES OF IMPACT RESISTANCE

In order to obtain corrected averages of impact resistance of notched Krouse specimens after runs of 400,000 cycles or more at ±40,000 lb/sq in. (batch 4), the average values for the specimens tested in impact were multiplied by the probability of fresh specimens surviving - that is, not fracturing completely in the fatigue machine. Of the 37 specimens used for attempted runs of 400,000 cycles or more, three specimens failed short of 400,000 cycles. The chance of survival was therefore 34/37 or 0.92. Similarly, the chance of fresh specimens surviving 500,000 cycles was 0.84 and for 600,000 cycles, the chance was 0.70.

APPENDIX B

EXAMINATIONS AND IMPACT-TEST RESULTS

Photographs of the roots of the notches of some individual Krouse specimens of batch 4 after stressing at ±40,000 lb/sq in., were taken after the repeated stress treatments but prior to impact testing. These photographs were taken by dark-field illumination and at 100 diam. Only the photographs of the 50,000-cycle group and the 400,000-cycle group are included in this paper and they appear as figures 23 and 24, respectively. Adjacent to the surface photographs are photographs showing the corresponding impact fractures at $7\frac{1}{2}$ diam. The white numerals identify the specimens. In each case the top side of the photograph of the fracture represents the tension side of the impact specimen.

The 50,000-Cycle Group

No cracks were found on any of the specimens of the 50,000-cycle group. There seemed to be no difference between the 50,000-cycle group and the unstressed specimens as shown by the photographs.

The 100,000-Cycle Group

The notch surfaces of the 100,000-cycle group appeared generally rougher than those of the 50,000-cycle group. Specimens 24A, 69A, and 89A were distinguished by coarse surface flaws probably left by incomplete polishing operations; however, if these specimens are omitted from consideration, the remaining specimens give average impact-resistance values of 85, 91, and 84 percent of the values for unstressed specimens at room temperature at -20° C, and at -78° C, respectively. This result strongly indicates that damage to impact resistance was actually due to repeated stressing and not to poor specimens. The beginning of cracks was strongly suggested by crooked rows of bright dots showing under dark field illumination in specimens 25, 30, and 42, and it seems significant that the impact resistances of these specimens were well below the averages for their respective groups. Crack walls could not be detected on the fracture areas after impact; therefore it is evident that the examination under dark field illumination of the polished surfaces was a very sensitive method for detecting the beginning of cracks.

The 200,000-, 300,000-, 400,000-, 500,000-, and 600,000-Cycle Groups

The 200,000-, 300,000-, 400,000-, 500,000-, and 600,000-cycle groups each contained specimens of which the results within the group pointed to one or the other or both of the following observations:

(a) Shallow cracks in specimens at −20° C and at −78° C were at least as injurious to impact resistance as cracks several times deeper in specimens at room temperature. The following example illustrating this statement is found in the 200,000-cycle group:

Specimen	Encircling crack, av. depth (mm)	Percentage of impact energy for unstressed specimens retained	Temperature of impact test
66A	0.50	55	Room
17A	.05	55	−20° C
43A	.05	37	−78° C

(b) A fairly large crack was more serious at low temperatures than a comparable crack at room temperature, the damage being calculated as percentage of the average value for unstressed specimens. The following example illustrating this statement is found in the 500,000-cycle group:

Specimen	Encircling crack, av. depth (mm)	Percentage of impact energy for unstressed specimens retained	Temperature of impact test
61A	0.55	58	Room
23A	.50	25	−20° C
47A	.50	7	−78° C
32A	.50	5	−78° C

REFERENCES

1. Staff of Battelle Memorial Institute: Prevention of the Failure of Metals under Repeated Stress. John Wiley & Sons, Inc., 1941.

2. Gough, H. J.: Crystalline Structure in Relation to Failure of Metals – Especially by Fatigue. A.S.T.M. Proc., vol. 33, pt. II, 1933, pp. 3–114.

3. Ewing, J. A., and Humfrey, J. C. W.: The Fracture of Metals under Repeated Stress. Phil. Trans. Roy. Soc. (London), vol. 200, ser. A, 1902, pp. 241–250.

4. Gough, H. J.: The Behavior of Metals Subjected to Repeated Stresses. Proc. Roy. Soc. (London), ser. A, vol. 104, no. 727, Nov. 1, 1923, pp. 538–565.

5. Barrett, C. S.: Structure of Iron after Compression. Trans. Am. Inst. Mining and Metallurgical Eng., vol. 135, 1939, pp. 296–324; discussion, pp. 324–326.

6. Wood, W. A., and Thorpe, P. L.: Behavior of the Crystalline Structure of Brass under Slow and Cyclic Stresses. Proc. Roy. Soc. (London), ser. A, vol. 174, no. 958, Feb. 21, 1940, pp. 310–321.

7. Fischer, M. F.: Note on the Effect of Repeated Stresses on the Magnetic Properties of Steel. Res. Paper RP26, Bur. of Standards Jour. Res., vol. 1, no. 5, 1928, pp. 721–732.

8. Davidenkow, N., and Schewandin, E.: Über den Ermüdungsriss. Metallwirtschaft, vol. 10, no. 37, Sept. 11, 1931, pt. II, pp. 710–714.

9. French, H. J.: Fatigue and Hardening of Steels. Trans. Am. Soc. Steel Treating, vol. 21, no. 10, Oct. 1933, pp. 899–946.

10. Kommers, J. B.: The Effect of Overstressing and Understressing in Fatigue. Trans. A.S.T.M., vol. 38, pt. II, 1938, pp. 249–262.

11. Müller-Stock, H.: Der Einfluss dauernd und unterbrochen wirkender, schwingender Überbeanspruchung auf die Entwicklung des Dauerbruchs. Mitteilungen der Kohle- und Eisenforschung, vol. 2, no. 2, March 1938, pp. 83–107.

12. Müller-Stock, H., Gerold, E., and Schulz, E. H.: Der Einfluss einer Wechselvorbeanspruchung auf Biegezeit- und Biegewechselfestigkeit von Stahl St. 37. Archiv für das Eisenhüttenwesen, vol. 12, no. 3, Sept. 1938, pp. 141-148.

13. Russell, H. W., and Welcker, W. A., Jr.: Damage and Overstress in the Fatigue of Ferrous Metals, A.S.T.M. Proc., vol. 36, pt. II, 1936, pp. 118-138.

14. Oshiba, F.: The Degree of Fatigue and Recovery Therefrom of Carbon Steels under Repeated Impacts, Sci. Rep. of Tohoku Imperial Univ. (Sendai, Japan), 1st ser., vol. 23, no. 4, Nov. 1934, pp. 589-611.

15. Oshiba, F.: The Degree of Fatigue of Carbon Steels under Reversed Bendings. Sci. Rep. of Tohoku Imperial Univ. (Sendai, Japan), 1st ser., vol. 26, no. 3, Dec. 1937, pp. 323-340.

16. Kies, J. A., and Quick, G. W.: Effect of Service Stresses on Impact Resistance, X-Ray Diffraction Patterns, and Microstructure of 25S Aluminum Alloy. Rep. No. 659, NACA, 1939.

17. Portevin, A. M.: Toughness (Impact Strength) Unaffected by Alternating Stresses (Fatigue). Metal Progress, vol. 37, no. 5, May 1940, pp. 563-564.

18. McAdam, D. J., Jr., and Clyne, R. W.: Theory of Impact Testing: Influence of Temperature, Velocity of Deformation, and Form and Size of Specimen on Work of Deformation. A.S.T.M. Proc., vol. 38, pt. II, 1938, pp. 112-134.

19. Rosenberg, Samuel J.: Effect of Low Temperatures on the Properties of Aircraft Metals. Res. Paper RP1347, Nat. Bur. of Standards Jour. Res., vol. 25, no. 6, Dec. 1940, pp. 673-701.

20. Anon.: Report of Research Committee on Fatigue of Metals. A.S.T.M. Proc., vol. 35, pt. I, 1935, p. 116.

21. France, R. D.: Endurance Testing of Steel: Comparison of Results Obtained with Rotating-Beam versus Axially-Loaded Specimens. A.S.T.M. Proc., vol. 31, pt. II, 1931, pp. 176-191.

22. Orowan, E.: Theory of the Fatigue of Metals. Proc. Roy. Soc. (London), ser. A, vol. 171, no. 944, May 1, 1939, pp. 79-106.

23. Gough, H. J., and Wood, W. A.: The Crystalline Structure of Steel at Fracture. Proc. Roy. Soc. (London) ser. A, vol. 165, no. 922, Apr. 14, 1938, pp. 358-371.

24. Daeves, Karl, Gerold, E., and Schulz, E. H.: Beinflussung der Lebensdauer wechselbeanspruchter Teile durch Ruhepausen. Stahl und Eisen, vol. 60, no. 5, Feb. 1, 1940, pp. 100-103.

25. Schulz, E. H., and Püngel, W.: Beiträge zur Ermüdungsprobe von Stahl auf dem Kruppschen Dauerschlagwerk. Mitteilungen aus der Versuchsanstalt der Deutsch-Luxemburgischen Bergwerks- und Hütten-Aktiengesellschaft - Abt. Dortmunder Union, vol. 1, no.2, Oct., 1922, pp. 43-51.

26. Bollenrath, F.: Zeit- und Dauerfestigkeit der Werkstoffe. Ergänzungsband of Jahrb. 1938 der deutschen Luftfahrtforschung. R. Oldenbourg (Munich), pp. 147-157.

27. Stodola, A.: Steam and Gas Turbines. Vol. I. McGraw-Hill Book Co., Inc., 1927.

TABLE I.- MANUFACTURER'S ANALYSES OF SAE X4130 STEELS USED

[Hot-rolled bars, 1/2 in. square]

Manufacturer's number	Grain size	Composition (percent)						
		Carbon	Manganese	Phosphorus	Sulphur	Silicon	Chromium	Molybdenum
21J021	6-8	0.29	0.54	0.018	0.018	0.19	0.89	0.16
21J023	5-7	.30	.49	.017	.017	.26	.95	.23
4H598	5-7	.31	.57	.015	.020	.020	1.01	.25

TABLE II.- TENSILE PROPERTIES AND HARDNESS NUMBERS OF NINE NORMALIZED BATCHES OF SAE X4130 STEEL

[Tensile specimens 0.250 in. in diameter except as noted]

Batch	Manufacturer's number	Yield strength at 0.02 percent offset (lb/sq in.)	Ultimate tensile strength (lb/sq in.)	True breaking stress[1] (lb/sq in.)	Elongation in 2 inches (percent)	Reduction of area (percent)	Vickers number, 45 kg load
[2]1	21J021	70,000	114,500	181,000	11.7	50.0	222
2	21J021	68,600	113,500	191,400	16.3	49.4	233
[2]3	21J021	71,000	118,200	180,000	17.5	45.7	234
4	21J021	66,500	118,800	185,000	15.8	48.0	242
5	21J023	84,300	130,600	222,000	15.8	54.6	287
6	21J023	89,000	130,400	221,000	16.3	54.7	283
7	21J023	86,000	131,000	221,000	15.5	54.2	279
8	4H598	80,000	128,100	211,400	13.8	52.0	284
9	4H598	65,800	116,000	190,800	16.8	49.0	238

[1] Load at fracture divided by minimum cross section measured after fracture.

[2] Test specimens 0.200 in. in diameter.

TABLE III.– TRANSVERSE IMPACT RESISTANCE OF NORMALIZED SAE X4130 STEEL AFTER REPEATED STRESS BELOW OR IN THE FATIGUE-LIMIT RANGE

[Krouse machine; notched rotating cantilever-beam fatigue specimens]

Specimen	Steel batch	Notch: Depth (in.)	Notch: Root radius (in.)	Fatigue limit (lb/sq in.)	Extreme-fiber stress (lb/sq in.)	Cycles of stress	Transverse impact resistance (ft/lb)
Impact tests at room temperature							
KN 1	1	0.035	0.020	33,000	0	0	9.6
KN 8				33,000	0	0	9.5
KN 3				33,000	±28,000	11.0×10^6	9.8
KN 4				33,000	±28,000	10.8	11.4
KN 6				33,000	±28,000	23.6	9.2
Impact tests at -78° C							
SKN 29	1	0.040	0.010	26,500	0	0	2.5
SKN 31				26,500	0	0	1.6
SKN 18				26,500	±25,000	41.1×10^6	1.7
SKN 24				26,500	±26,000	23.7	2.6
SKN 27				26,500	±26,600	54.4	1.4
SKN 102	2	.040	.010	35,000	0	0	1.2
SKN 103				35,000	0	0	1.1
SKN 75				35,000	±33,500	10.5	1.1
SKN 68	2	.040	.020	36,000	0	0	1.6
SKN 49				36,000	±33,700	40.0	1.1
SKN 52				36,000	±36,000	23.8	2.2

TABLE IV.- TENSILE IMPACT RESISTANCE OF NORMALIZED SAE X4130 STEEL (BATCH 7)

STRESSED AS ROTATING BEAM WITHIN THE FATIGUE-LIMIT RANGE

[R. R. Moore fatigue testing machine; unnotched specimens;
fatigue limit, 60,000 lb/sq in.]

Specimen	Stress (lb/sq in.)	Cycles	Tensile impact test	
			Energy (ft-lb)	Elongation in 2 inches (in.)
Impact tests at room temperature				
MI 2	±62,000	$20,660 \times 10^3$	53.5	0.155
MI 1	±61,000	20,640	50.8	.155
MI 10	±61,000	23,156	56.2	.157
MI 13	±60,000	22,667	47.4	.155
MI 18	±59,000	20,286	53.5	.155
MI 20	0	0	51.7	.155
Impact tests at -33° C				
MI 5	±62,000	$20,606 \times 10^3$	54.4	0.150
MI 9	±61,000	23,160	51.7	.145
MI 12	±61,000	23,358	51.7	.147
MI 16	±60,000	20,558	56.2	.145
MI 19	±59,000	20,443	52.6	.145
HI 68	0	0	53.5	.145

TABLE V.- TENSILE IMPACT RESISTANCE OF FATIGUE SPECIMENS OF SAE X4130 STEEL AFTER REPEATED AXIAL STRESS BELOW THE FATIGUE LIMIT

[Haigh machine; impact tests at room temperatures]

Specimen	Steel batch	Minimum diameter of specimen	Surface finish	Mean tensile stress (lb/sq in.)	Total stress amplitude (lb/sq in.)	Cycles of stress	Fatigue-limit amplitude (lb/sq in.)	Impact energy (ft-lb)
HI 7	1	0.200	Aloxite	0	93,000	$10,488 \times 10^3$	96,000 >F.L. >93,000	54.4
HI 8				0	93,000	9,996	96,000 >F.L. >93,000	51.7
HI 18				0	81,800	17,628	96,000 >F.L. >93,000	54.4
HI 20				0	81,800	14,004	96,000 >F.L. >93,000	51.7
HI 1			4/0	(1)	(1)	(1)	96,000 >F.L. >93,000	54.4
HI 2				(1)	(1)	(1)	96,000 >F.L. >93,000	50.8
HI 3				(1)	(1)	(1)	96,000 >F.L. >93,000	50.0
HI 4				(1)	(1)	(1)	96,000 >F.L. >93,000	50.0
HI 5				(1)	(1)	(1)	96,000 >F.L. >93,000	54.4
HI 6				(1)	(1)	(1)	96,000 >F.L. >93,000	52.6
HSF 11	2	.170	Aloxite	17,400	88,800	20,551	88,800	34.3
HSF 12				(1)	(1)	(1)	88,800	34.8
HSF 15	3			17,400	87,700	34,128	87,700	35.1
HSF 18				17,400	87,700	24,115	87,700	33.7

---

[1] Not stressed.

TABLE VI.– AVERAGE TRANSVERSE IMPACT RESISTANCE OF NORMALIZED SAE X4130 STEEL (BATCH 4) AFTER VARIOUS STAGES OF REPEATED STRESS

[Krouse machine, notched rotating-cantilever-beam fatigue specimens, notch, depth = 0.040 in., root radius, 0.010 in., nominal fatigue limit, 26,000 lb/sq in., nominal maximum fiber stress, 40,000 lb/sq in.]

Temperature of impact test	Average impact resistance															
	Not stressed		After 50,000 cycles		After 100,000 cycles		After 200,000 cycles		After 300,000 cycles		After 400,000 cycles		After 500,000 cycles		After 600,000 cycles	
	(ft-lb)	(percent) (1)	(ft-lb)	(percent)	(ft-lb)	(percent)	(ft-lb)	(percent)	(ft-lb)	(percent)	(ft-lb)	(percent)	(ft-lb)	(percent)	(ft-lb)	(percent)
Room	2.42	100	2.37	98	1.91	79	1.82	75	1.44	60	1.21	50	1.23	51	0.84	35
-20° C	1.70	100	1.94	114	1.50	88	1.18	69	1.11	65	.37	22	.35	20	.11	6
-78° C	.99	100	.73	74	.79	80	.64	65	.27	27	.32	32	.11	11	.23	23

[1] Value for specimens that had not been fatigue-stressed used as base.

TABLE VII.- TRANSVERSE IMPACT RESISTANCE OF NORMALIZED SAE X4130 STEEL (BATCH 1) AFTER REPEATED STRESS 26 PERCENT ABOVE THE FATIGUE LIMIT

[Krouse machine; notched rotating-cantilever-beam specimens; notch, depth = 0.040 in., root radius = 0.010 in.; fatigue limit, 26,600 lb/sq in.; nominal maximum fiber stress, 33,500 lb/sq in.]

Specimen	Cycles of stress	Impact resistance (ft/lb)
Impact test at room temperature		
SKN 22	0	6.4
SKN 32	0	5.1
SKN 5	100,000	5.5
SKN 10	100,000	3.4
SKN 11	100,000	5.4
SKN 6	200,000	5.6
SKN 12	259,000	5.0
SKN 3	346,000	3.1
SKN 8	405,000	4.7
SKN 4	620,000	2.2
Impact test at -78° C		
SKN 29	0	2.5
SKN 31	0	1.6
SKN 30	200,000	1.4
SKN 28	377,000	.3
SKN 20	500,000	.2
SKN 1	[1]494,000 F	0
SKN 9	506,000 F	0
SKN 2	516,000 F	0

[1] The letter F indicates complete fracture in fatigue machine.

TABLE VIII.- TRANSVERSE IMPACT RESISTANCE OF NORMALIZED SAE X4130 STEEL (BATCH 2) AFTER REPEATED STRESS 43 PERCENT ABOVE THE FATIGUE LIMIT

[Krouse machine; notched rotating-cantilever-beam specimens; notch, depth = 0.040 in., root radius, 0.010 in.; fatigue limit, 28,000 lb/sq in.; nominal maximum fiber stress, 40,000 lb/sq in.]

Specimen	Cycles of stress	Impact resistance (ft-lb)
Impact test at room temperature		
SKN 95	0	5.3
SKN 104	0	3.4
SKN 87	100,000	4.1
SKN 89	100,000	5.3
SKN 91	100,000	4.3
SKN 86	200,000	3.3
SKN 88	200,000	2.2
SKN 90	200,000	1.7
Impact test at -78° C		
SKN 100	0	0.9
SKN 102	0	1.2
SKN 103	0	1.1
SKN 93	100,000	1.0
SKN 98	100,000	.8
SKN 101	100,000	1.2
SKN 92	200,000	1.3
SKN 96	200,000	1.4
SKN 97	200,000	.2
SKN 99	200,000	1.3
SKN 69	500,000	.1
SKN 70	500,000	.1
SKN 68	600,000	.1
SKN 71	[1]333,000 F	0
SKN 72	450,000 F	0
SKN 67	668,000 F	0

[1] The letter F indicates complete fracture.

TABLE IX.- RESULTS OF TENSILE IMPACT TESTS OF NORMALIZED SAE X4130 STEEL (BATCH 9) AFTER FATIGUE-STRESSING IN EQUAL TENSION AND COMPRESSION

[Haigh machine; minimum diameter of specimens, 0.180 in.; aloxite finish]

Specimen	Stress amplitude (lb/sq in.)	Cycles	Visual examination before impact test[1]	Impact energy (ft-lb)	Elongation in 2 inch gage length (in.)	Damage detection after impact test		
						Surface cracks	Impact energy loss	Elongation loss
HI 1c	±57,200	4.8×10^3	Buckled	--------	-------	-------	-------	----------
HI 5c	±52,000	91.2	F, h.c.	--------	-------	-------	-------	----------
HI 10c	±50,000	52.2	F, h.c.	--------	-------	-------	-------	----------
HI 13c	±49,500 ±49,000	7.2 40.8	F, h.c.	--------	-------	-------	-------	----------
HI 16c	±49,000	124.8	F	--------	-------	-------	-------	----------
HI 12c	±49,000	129.6	Buckled	--------	-------	-------	-------	----------
HI 26c	±48,750	96.0	F	--------	-------	-------	-------	----------
Impact tests at -33° C								
HI 4c	±52,400	100.8×10^3	h.c.	44.0	0.130	Yes	No	No
HI 7c	±51,000	72.0	h.c.	45.3	.137	--do--	--do--	Do.
HI 9c	±51,000	60.0	h.c., c.	21.4	.55	--do--	Yes	Yes
HI 27c	±48,750	72.0	OK	44.0	.130	--do--	No	No
HI 28c	±48,750	36.0	OK	46.5	.145	--do--	--do--	Do.
HI 3c	±50,500 ±51,850	100.4 129.6	h.c.	41.9	.120	No	--do--	Do.
HI 6c	±51,000	12.0	h.c., buckled	45.7	.140	--do--	--do--	Do.
HI 8c	±51,000	12.0	h.c.	45.3	.140	--do--	--do--	Do.
HI 15c	±50,000	24.0	OK	41.5	.130	--do--	--do--	Do.
HI 20c	±49,000	72.0	OK	42.3	.130	--do--	--do--	Do.
HI 21c	±49,000	72.0	OK	43.6	.130	--do--	No	Do.
HI 17c	±49,000	24.0	h.c.	44.8	.142	--do--	--do--	Do.
HI 19c	±49,000	24.0	OK	43.6	.135	--do--	--do--	Do.
HI 23c	±48,750	72.0	OK	42.3	.130	--do--	--do--	Do.
HI 34c	±48,750	36.0	OK	41.1	.115	--do--	--do--	?
HI 36c	(2)	(2)	(2)	40.7	.125	-------	-------	----------
Impact tests at room temperature								
HI 2c	±48,275 ±50,000	144.0×10^3 12.0	h.c., c.	36.7	0.110	Yes	?	Yes
HI 25c	±48,500	480.0	OK	41.5	.140	--do--	No	No
HI 11c	±49,000	2744.0	OK	37.5	.130	No	--do--	Do.
HI 24c	±49,000	72.0	OK	41.5	.135	--do--	--do--	Do.
HI 22c	±49,000	72.0	OK	38.6	.130	--do--	--do--	Do.
HI 18c	±49,000	24.0	h.c.	44.0	.160	--do--	--do--	Do.
HI 23c	±49,000	24.0	h.c.	46.6	.152	--do--	--do--	Do.
HI 31c	±48,750	205.6	OK	39.1	.135	--do--	--do--	Do.
HI 29c	±48,750	72.0	OK	39.9	.145	--do--	--do--	Do.
HI 30c	±48,750	36.0	OK	38.6	.140	--do--	--do--	Do.
HI 32c	±48,750	4.8	Buckled	41.5	.165	--do--	--do--	Do.
HI 35c	(2)	(2)	------------	38.3	.135	-------	-------	----------

[1] The letter F indicates complete failure in fatigue machine; h.c., heat colored; c., fatigue crack or cracks; OK, no significant change in appearance.

[2] Not stressed.

TABLE X.- IMPACT RESISTANCE AT ROOM TEMPERATURE OF FATIGUE SPECIMENS OF NORMALIZED SAE X4130 STEEL STRESSED UNDER AXIAL LOADING

[0.200 in. in diam.; the surface layer containing fatigue cracks was machined off before impact test]

Specimen	Repeated stress		Observed surface condition after repeated stress	Specimen diameter after machining (in.)	Impact energy (ft/lb)	Surface condition after impact test
	Half range amplitude (lb/sq in.)	Mean stress tension (lb/sq in.)				
HSF 12	(1)	(1)	(1)	0.170	34.8	----------
HI 59	47,750	31,450	Surface cracks	.170	32.0	No cracks
HI 57	48,900	31,300	-------do-------	.170	28.8	Cracked
HSF 16	(1)	(1)	(1)	.150	26.1	No cracks
HI 65a	(1)	(1)	(1)	.150	26.9	Do.
HI 63	47,750	31,450	-------do-------	.150	25.0	No cracks
HI 13a	47,500	87,000	No cracks, necked slightly	.150	20.7	Do.
HI 19a	46,650	94,800	No cracks, necked slightly	.150	24.2	Do.
HI 54a	50,000	77,000	Surface cracks	.150	24.2	Cracked
HI 21a	50,000	77,000	No cracks seen	.150	22.8	Do.
HI 22a	50,000	77,000	-------do-------	.150	22.8	Do.
HI 24a	50,000	77,000	-------do-------	.150	21.4	Do.

[1] Not stressed.

TABLE XI.- THE EFFECT OF INTERMITTENT REST PERIODS ON THE ROTATING BEAM ENDURANCE OF NORMALIZED SAE X4130 STEEL (BATCH 5)

[All specimens fractured completely in the fatigue machine at the end of the runs noted, except specimens marked u which were removed uncracked; fatigue limit = 60,000 lb/sq in.]

Continuous runs		Intermittent runs			
Specimen	Total cycles	Specimen	Total runs	Total cycles	Daily number of cycles (thousands)
Extreme fiber stress, ±65,000 lb/sq in.					
R 3	$1,013\times10^3$	R 15	5	720×10^3	24 once; then 300 daily
Extreme fiber stress, ±64,000 lb/sq in.					
R 41	$1,080\times10^3$	R 12	9	$2,167\times10^3$	Increasing from 117 to 300
R 42	808				
R 43	1,315	R 13	22	1,058	29 first run; then 20 runs of 0.3 each with 5 sec. rest periods; then 969 last run
R 44	2,176				
Average	$1,345\times10^3$	R 14	7	1,851	Varying 136 to 340
		R 17	12	1,387	Increasing from 10 to 200
		R 18	8	1,092	140
		R 19	13	1,742	140
		R 45	26	1,446	54
		R 46	29	1,607	54
		R 47	19	1,190	65
		R 48	9	1,977	65 for 8 times; then 1463
		Average		$1,552\times10^3$	
Extreme fiber stress, ±63,500 lb/sq in.					
R 22	$1,632\times10^3$	[1]R 21	14	$3,243\times10^3$	Increasing from 130 to 300
		R 23	10	2,003	Increasing from 130 to 300
		Average		2,623	
Extreme fiber stress, ±63,000 lb/sq in.					
R 36	19,140 u	R 1	14	25,627 u	Increasing from 234 to 16,053
R 38	22,706 u	R 20	15	23,204 u	Increasing from 200 to 28,500
R 25	1,740	R 9	5	3,054	One run of 1040; then 540 daily
R 37	2,700	R 10	3	1,553	700
Average for fractured specimens	2,200	[2]R 20	10	1,857	Increasing from 134 to 300
		R 34	21	4,455	Increasing from 132 to 263
		R 49	20	1,331	66
		R 50	25	1,350	54
		R 51	16	909	
		Average for fractured specimens		2,120	

[1] Rested at 60° C for the remainder of each 24-hr period.

[2] Rested at 100° C for the remainder of each 24-hr period.

TABLE XII.- EFFECT OF LOW TEMPERATURE DURING FATIGUE-STRESSING BY FLEXURE ON THE IMPACT BEHAVIOR OF SPECIMENS OF NORMALIZED S.A.E. X4130 STEEL (BATCH 8)

[Rayflex machine; fatigue limits 51,000 lb/sq in. at room temperature and 63,500 lb/sq in. at -40° C as shown in fig. 22]

Number of specimens averaged	Temperature during fatigue (°C)	Fatigue-stressing: Average cycles run, a	Fatigue-stressing: Average crack-free endurance cycles, b	Fatigue-stressing: Average cycle ratio, a/b completed (percent)	Fatigue-stressing: Extreme-fiber stress (lb/sq in.)	Temperature impact (°C)	Average impact energy (ft-lb)	Tension side of specimen crack area (percent)	Compression side of specimen crack area (percent)	Fibrous area (percent)	Granular area (percent)
Specimens showing no cracks after repeated stress under magnaflux inspection[1]											
4	-40	$10,000 \times 10^3$	--------	-------	64,000	-78	41.2	0	0	30	70
6		333	1100×10^3	30	68,300		36.5	0	0	30	70
2		600	1100	55	68,300		41.9	0	0	40	60
4		10,000	--------	-------	64,000	Room	44.7	0	0	70	30
2	Room	10,000	--------	-------	52,000	-78	34.3	0	0	35	65
8		50	169	30	68,300		39.6	0	0	25	75
2		10,000	--------	-------	52,000	Room	38.9	0	0	85	15
4	(2)	(2)	(2)	(2)	(2)	(2)	41.9	0	0	35	65
3							46.0	0	0	85	15
Specimens showing cracks after repeated stress under magnaflux inspection[3]											
6	-40	----------	--------	-------	64,000 to 72,800	-78	0.6	45	0	0	55
8					64,000 to 79,600		.3	49	2	0	49
1					72,800	Room	4.0	35	10	20	35
2					72,800		2.9	32	0	30	38
1					72,800		.8	80	0	15	5
2					72,800	-78	16.8	0	45	15	40
1	Room	----------	--------	-------	58,000		18.5	0	40	20	40
3					63,700 to 72,800		1.6	5	3	0	92
4					63,700 to 72,800		1.1	15	11	0	73
4					55,750 to 64,900		.9	33	0	0	67
9					52,300 to 72,800		.4	35	1	0	64
4					63,700 to 72,800	Room	15.4	10	2	80	8
3					63,700		8.7	15	0	70	15
4					63,700 to 72,800		4.9	30	5	30	35

---

[1] Groups of specimens averaged were divided according to percentage of granular and fibrous areas of the fractures after separations according to temperatures.

[2] Not stressed.

[3] Groups of specimens averaged were divided according to impact energy after separations according to temperatures and location of cracks.

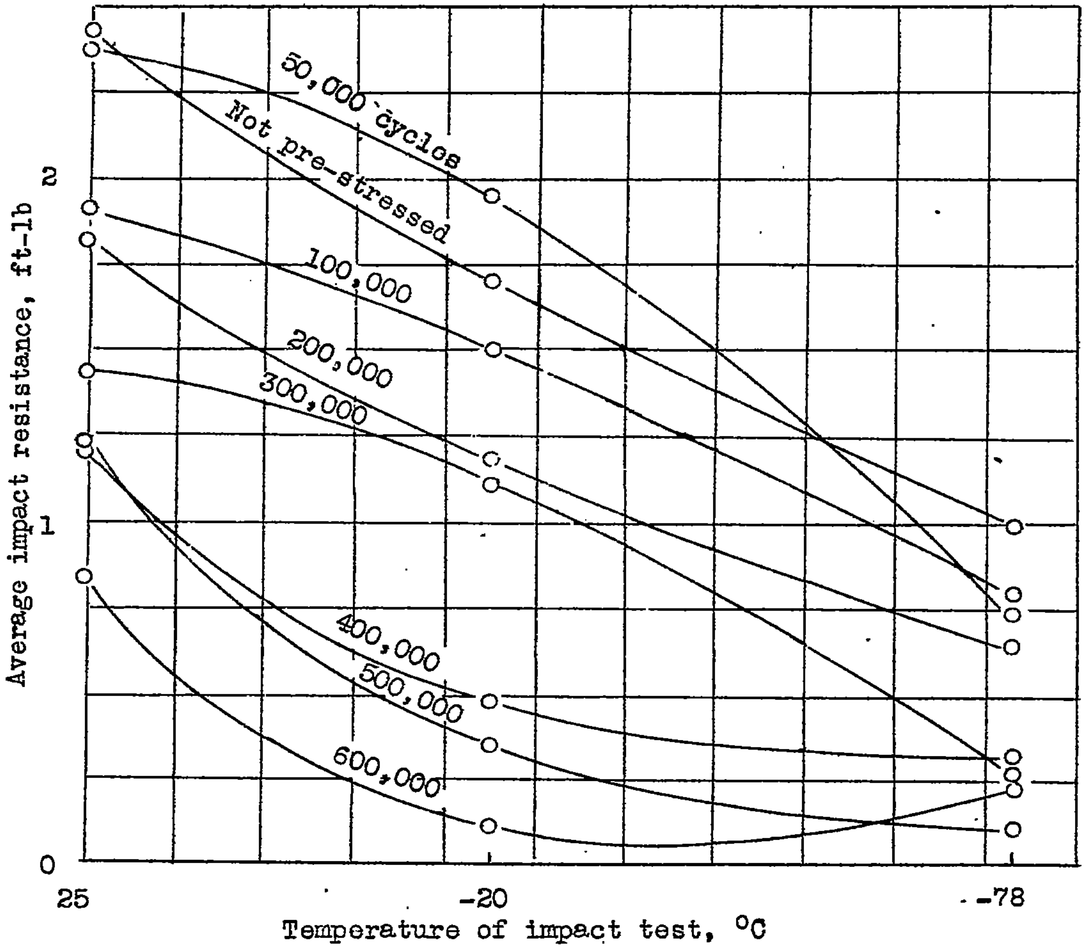


Figure 1.- Effect of temperature on the average transverse impact resistance of notched specimens of normalized S.A.E. X4130 steel (batch 4) after repeated stressing as rotating cantilever beams in the Krouse machine. Nominal stress amplitude, ±40,000 pounds per square inch; nominal fatigue limit, 26,600 pounds per square inch. Each point on the 25°C line represents two to four specimens; all other points each represent four specimens.

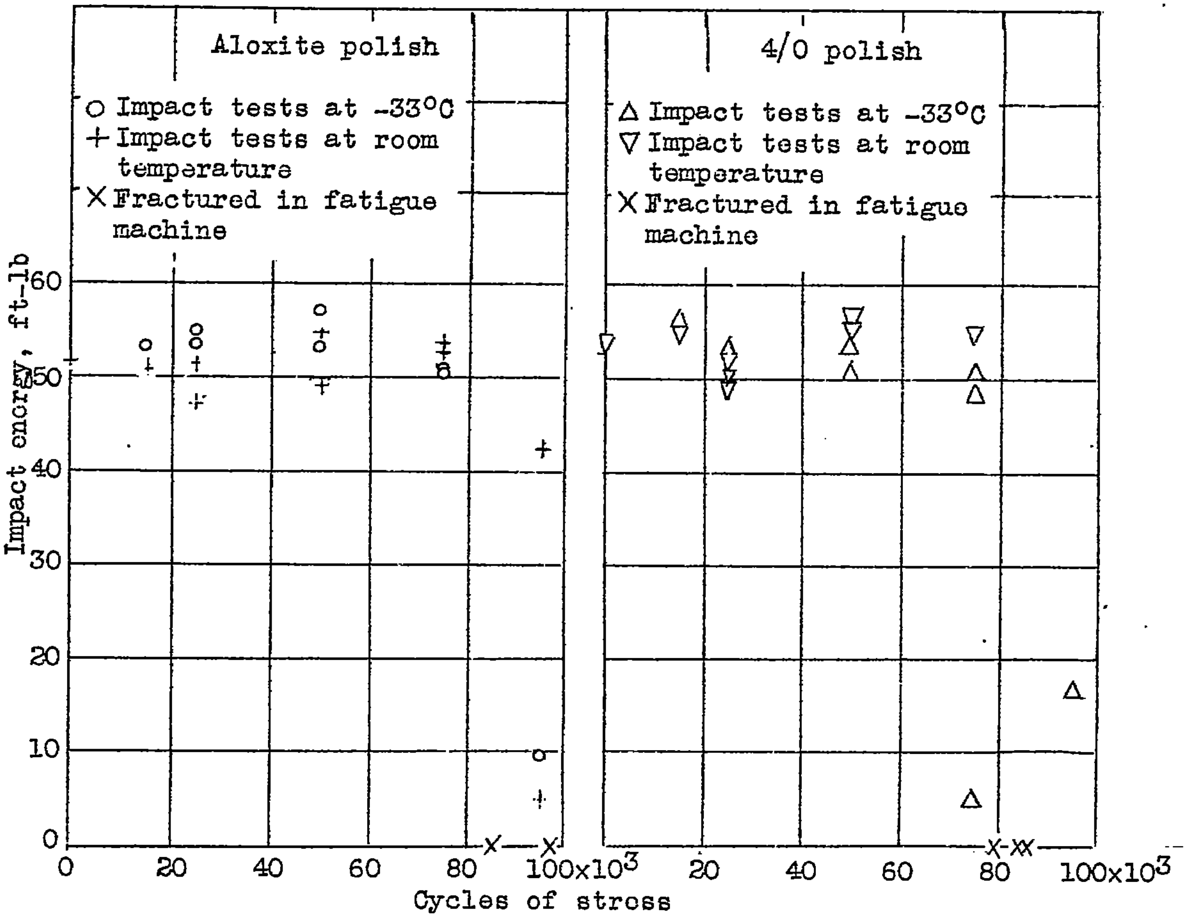


Figure 2.- Impact energy absorbed in tensile impact tests of specimens of normalized S.A.E. X4130 steel (batch 7) fatigue-stressed at ±80,000 pounds per square inch as rotating beams in R.R. Moore machine. Fatigue limit, 62,000 pounds per square inch. Each point represents one specimen.

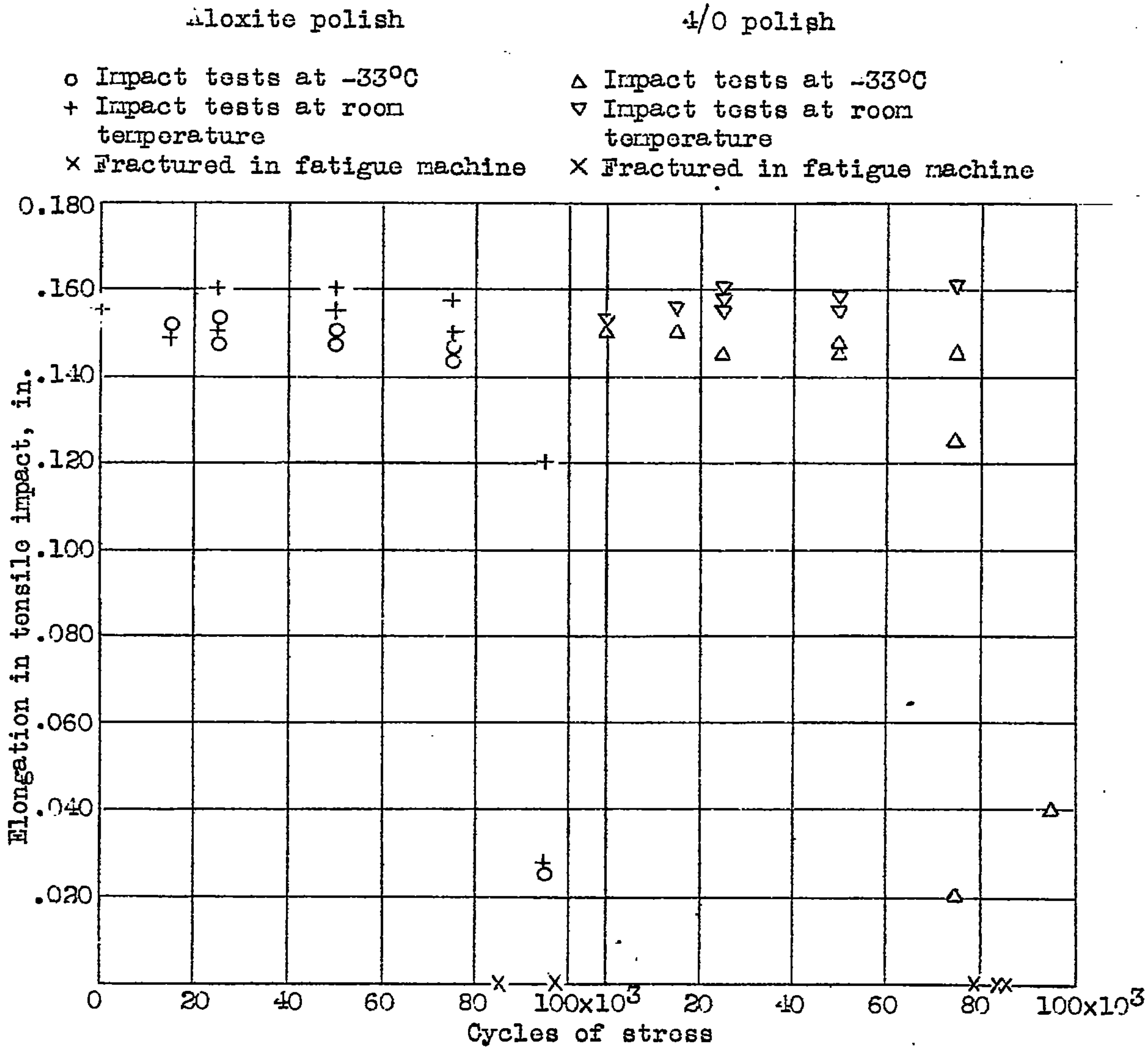


Figure 3.- Elongation in 2-inch gage length in tensile impact tests of specimens of normalized S.A.E. X4130 steel (batch 7) fatigue-stressed at ±80,000 pounds per square inch as rotating beams in R.R. Moore machine. Fatigue limit, 59,000 to 62,000 pounds per square inch. Each point represents one specimen.

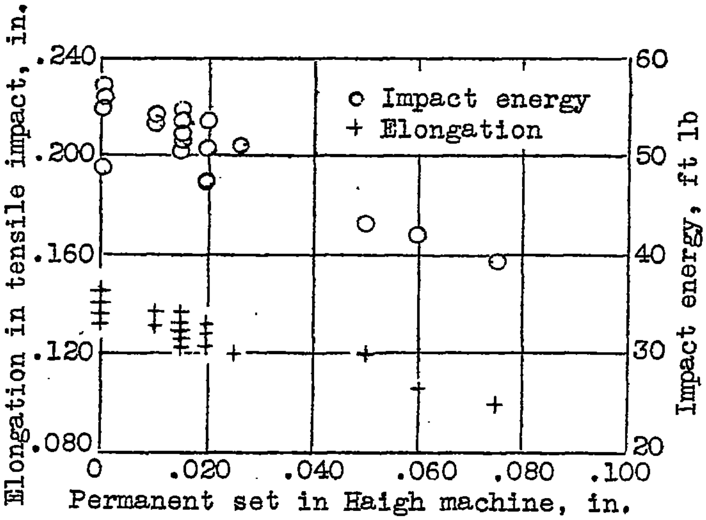


Figure 4.- Effects of varying amounts of permanent set during repeated stress under axial loading in the Haigh machine on the tensile impact properties of specimens of normalized S.A.E. X4130 steel (batch 9) at -33°C.

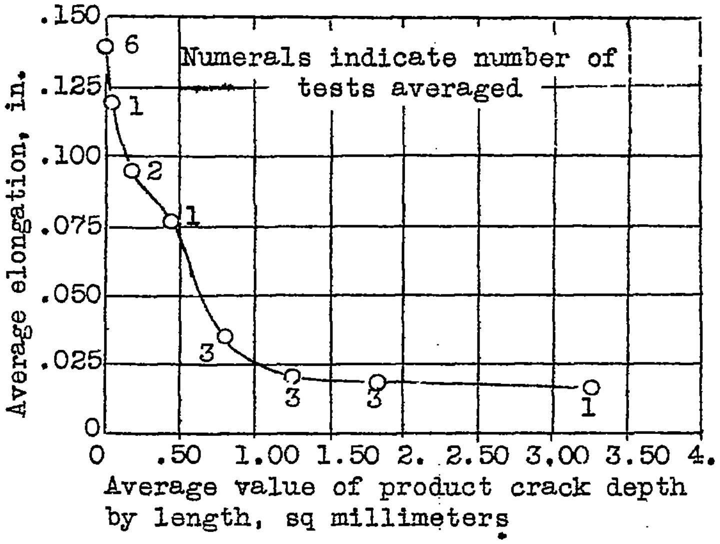


Figure 17.- Variation of average elongation during impacts with approximate crack area in fatigued specimens of normalized S.A.E. X4130 steel broken under tensile impact at -33°C.

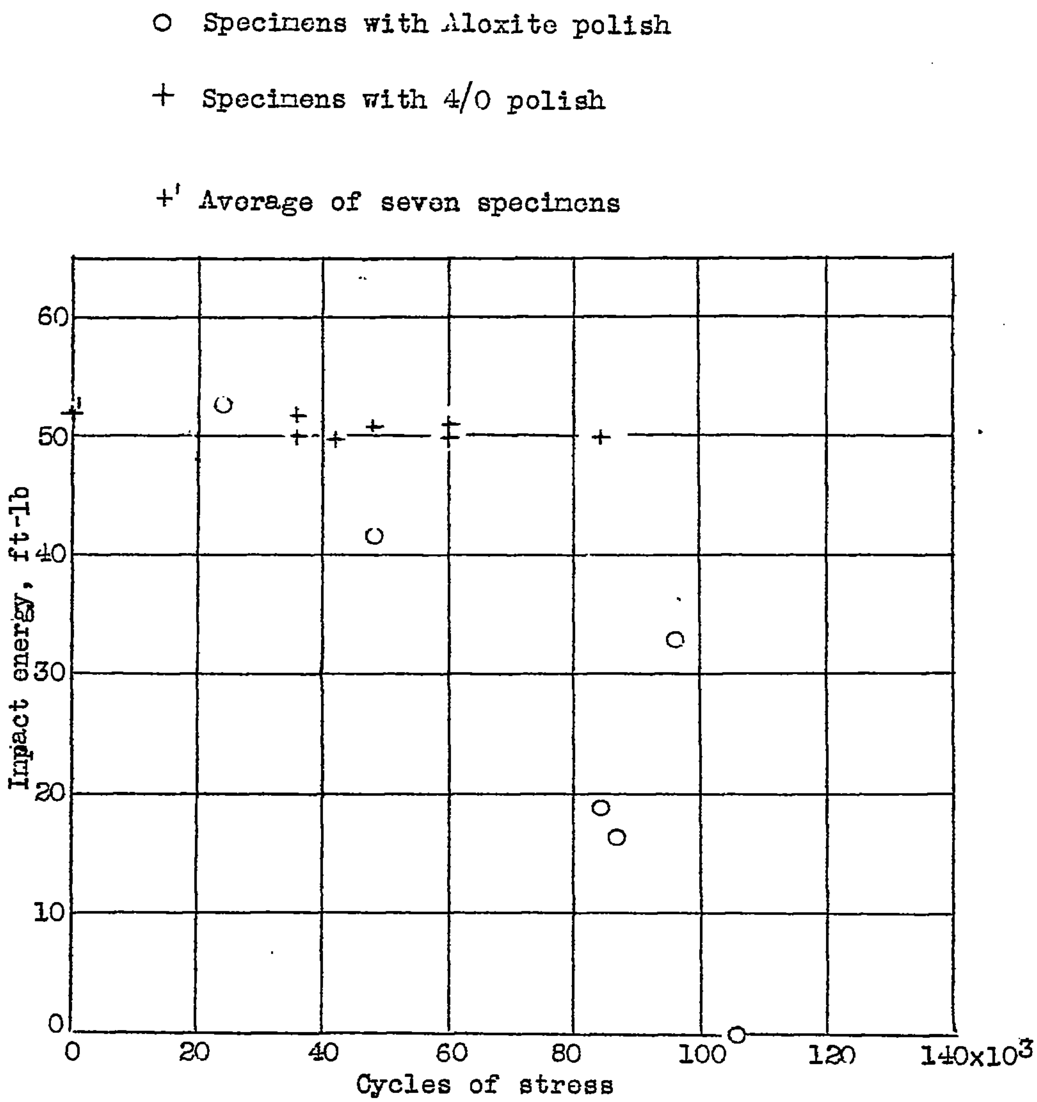


Figure 5.- Impact energy absorbed at room temperature in tensile impact tests of specimens of normalized S.A.E. X4130 steel (batch 1) fatigue-stressed by axial loading in the Haigh machine from 28,800 pounds per square inch compression to 63,000 pounds per square inch tension for various numbers of cycles. Minimum diameter, 0.200 inch.

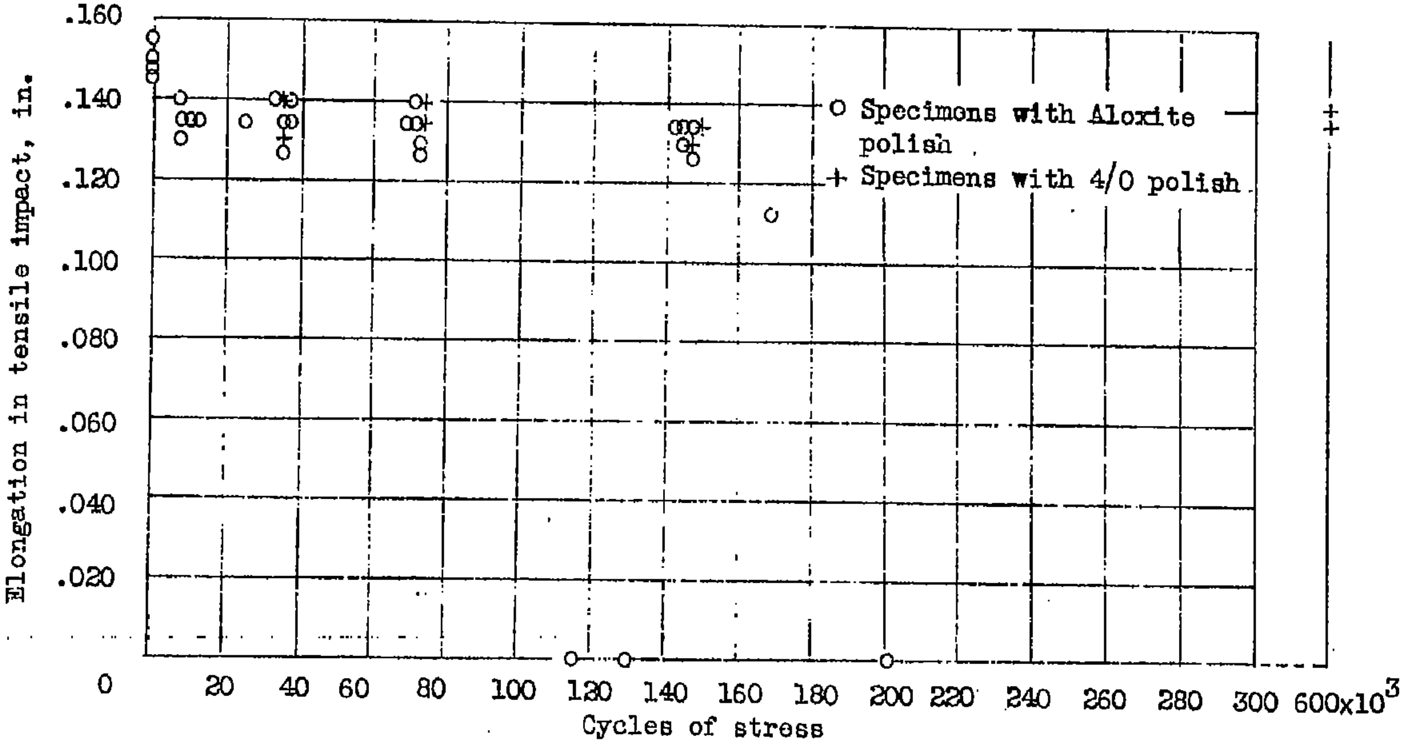


Figure 6.- Elongation in 2-inch gage length during tensile impact tests at room temperature of specimens of normalized S.A.E. X4130 steel (batch 9) after fatigue stressing under axial loading in the Haigh machine in tension ranging from 10,500 to 89,500 pounds per square inch (mean stress, 50,000 lb/sq in.).

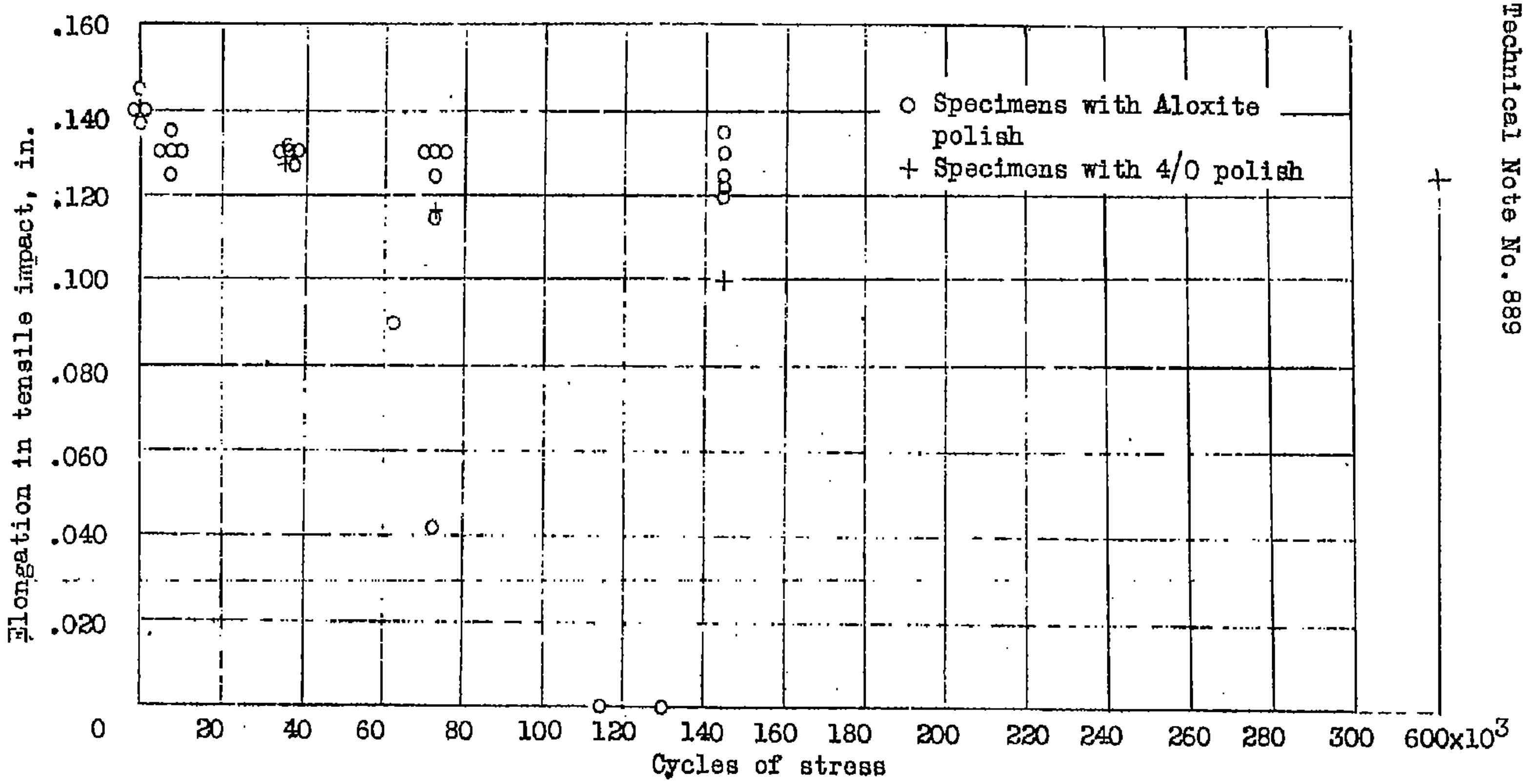


Figure 7.- Elongation in 2-inch gage length during tensile impact tests at -33°C of specimens of normalized S.A.E. X4130 steel (batch 9) after fatigure-stressing under axial loading in the Haigh machine in tension ranging from 10,500 to 89,500 pounds per square inch (mean stress, 50,000 lb/sq in.).

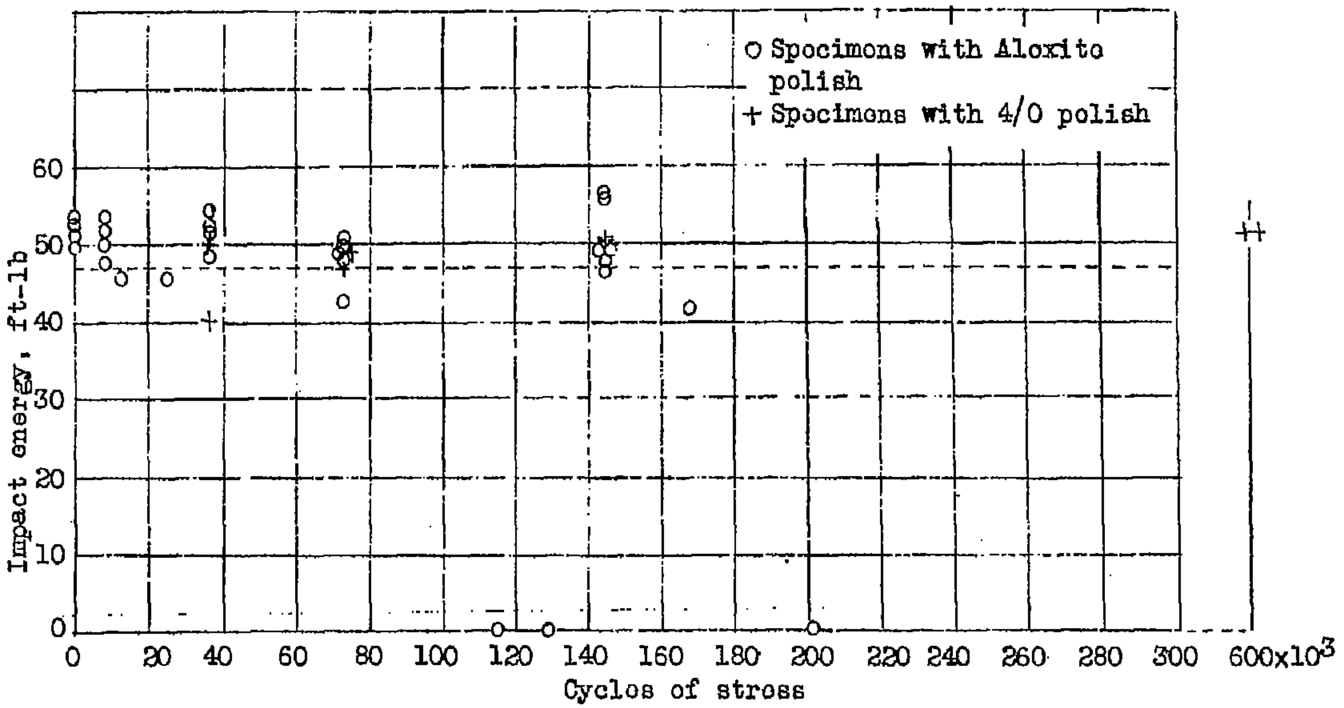


Figure 8.- Impact energy absorbed in tensile impact tests at room temperature of specimens of normalized S.A.E. X4130 steel (batch 9) after fatigue-stressing under axial loading in the Haigh machine in tension ranging from 10,500 to 89,500 pounds per square inch (mean stress, 50,000 lb/sq in.)

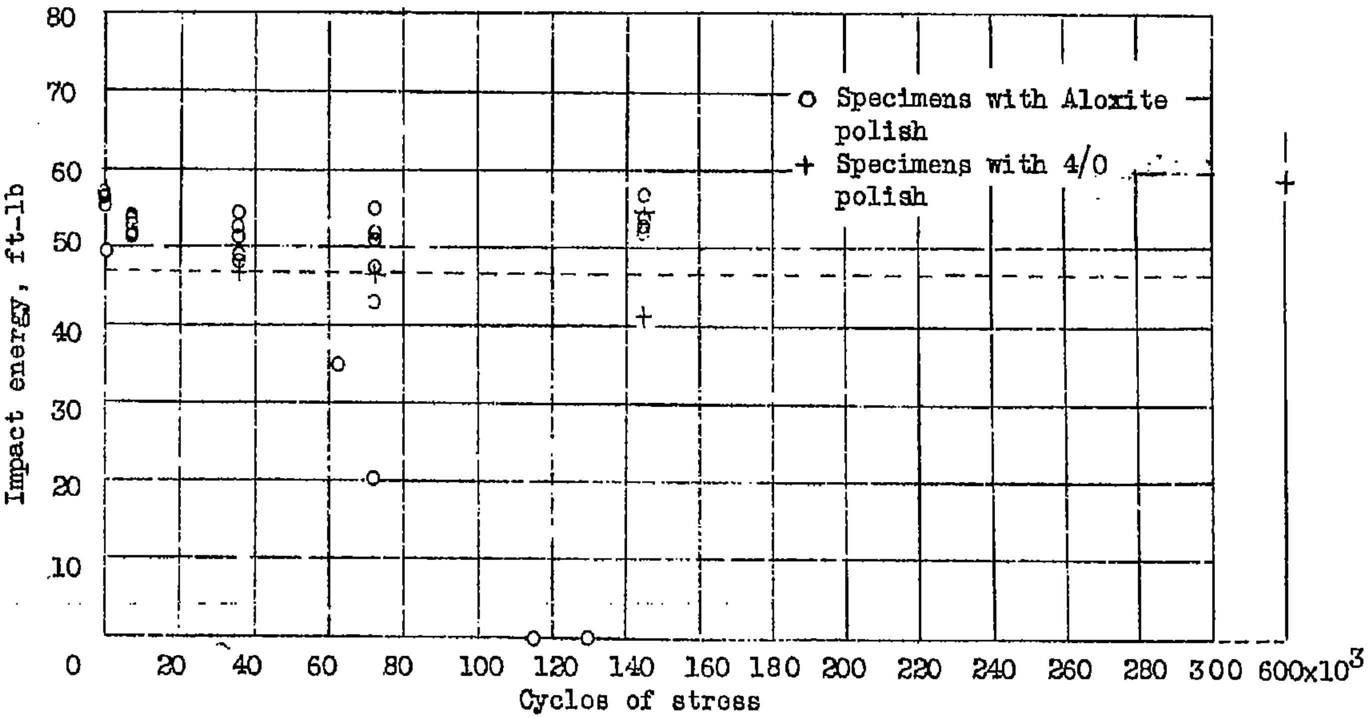


Figure 9.- Impact energe absorbed in tensile impact tests at -33°C of specimens of normalized S.A.E. X4130 steel (batch 9) after fatigure-stressing under axial loading in the Haigh machine in tension ranging from 10,500 to 89,500 pounds per square inch (mean stress, 50,000 lb/sq in.).

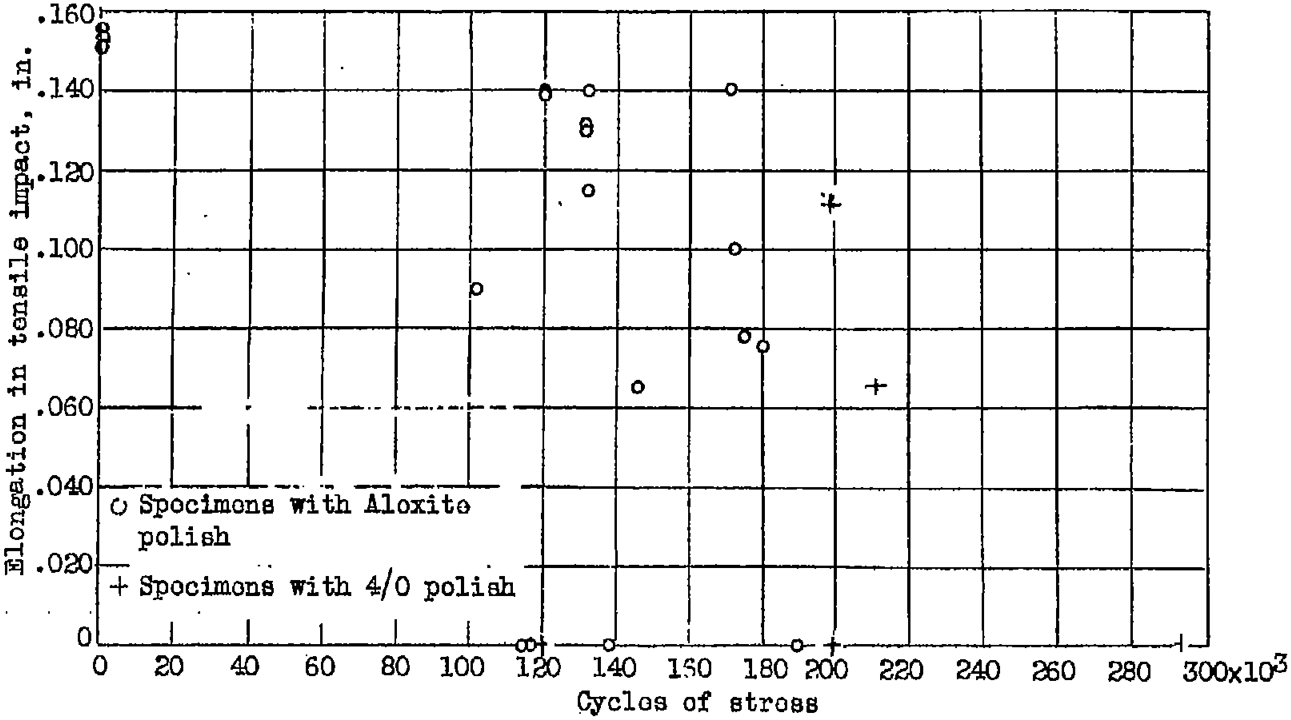


Figure 10.- Elongation in 2-inch gage length during tensile impact tests at room temperature of specimens of normalized S.A.E. X4130 steel (batch 6) after fatigue-stressing in the Haigh machine in axial tension ranging from 27,000 to 127,000 pounds per square inch for various numbers of cycles. Minimum diameter of specimen, 0.200 inch. Each point represents one specimen.

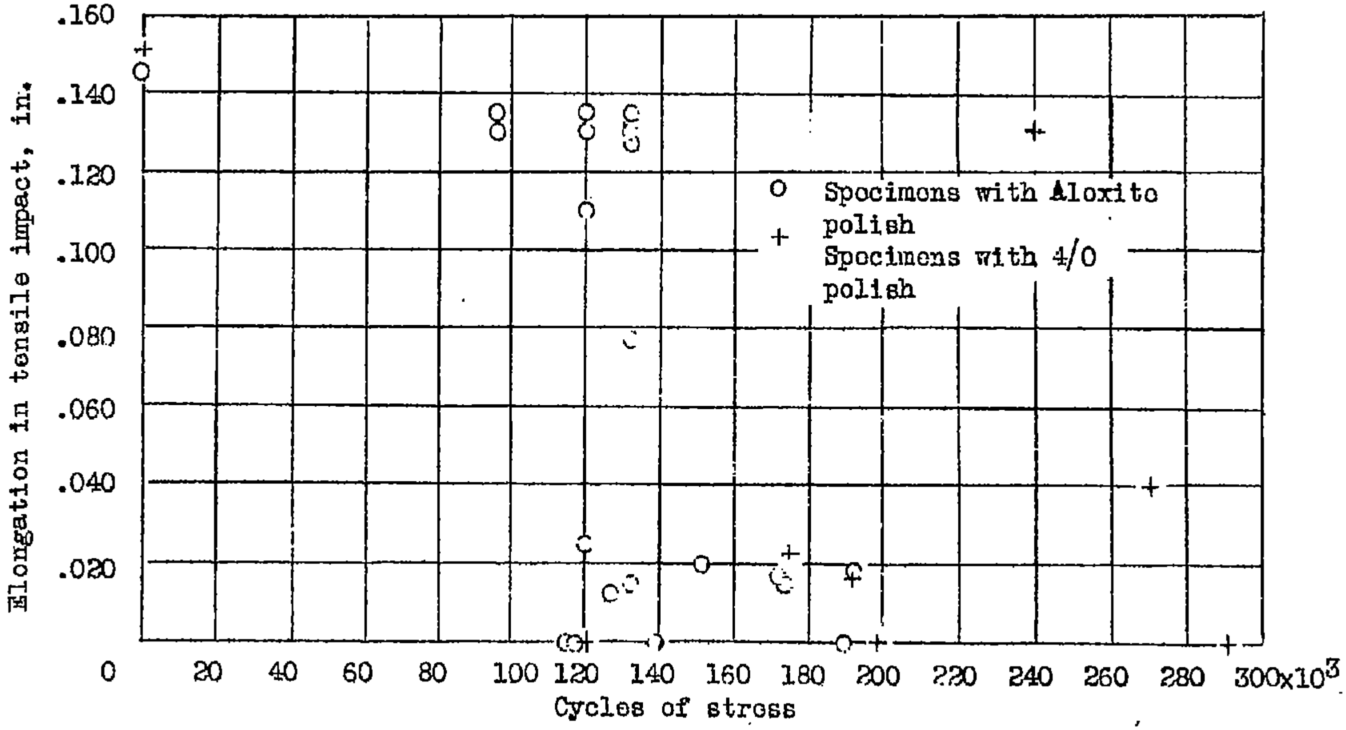


Figure 11.- Elongation in 2-inch gage length during tensile impact tests at -33°C of specimens of normalized S.A.E. X4130 steel (batch 6) after fatigure-stressing in the Haigh machine in axial tension ranging from 27,000 to 127,000 pounds per square inch for various numbers of cycles. Each point represents one test specimen.

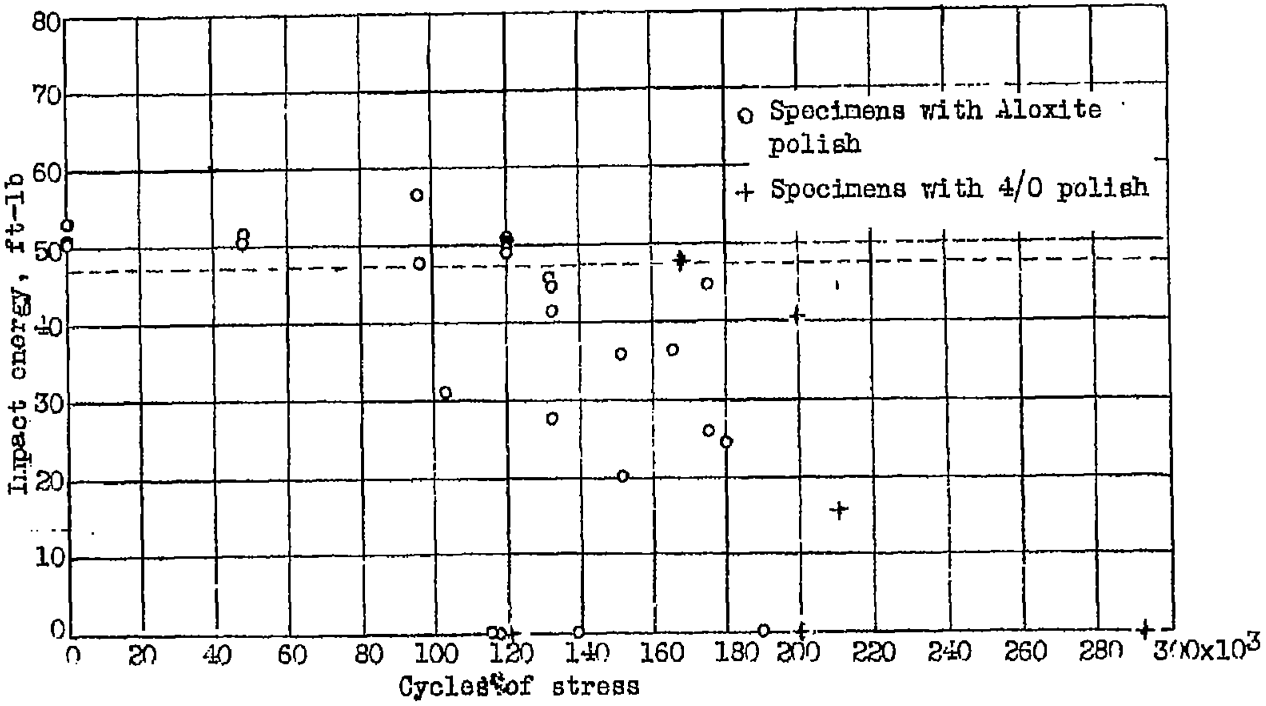


Figure 12.- Impact energy absorbed in tensile impact tests at room temperature of specimens of normalized S.A.E. X4130 steel (batch 6) after fatigue-stressing in the Haigh machine in axial tension ranging from 27,000 to 127,000 pounds per square inch for various numbers of cycles. Each point represents one specimen.

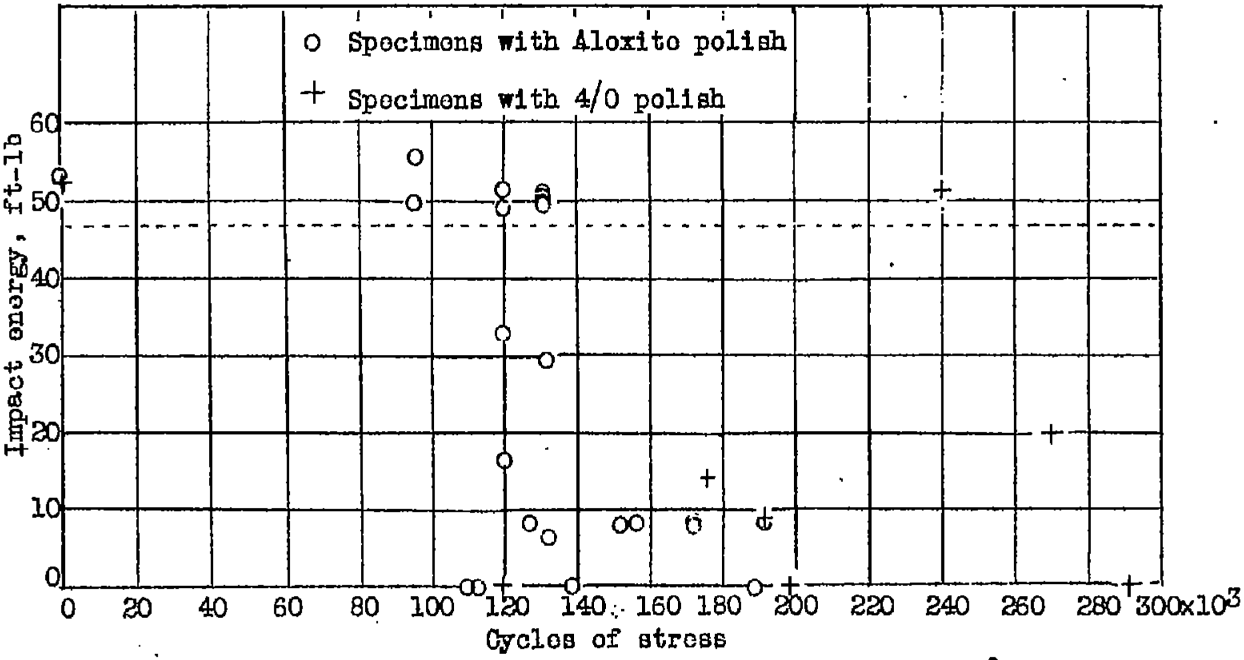


Figure 13.- Impact energy absorbed in tensile impact tests at -33°C of specimens of normalized S.A.E. X4130 steel (batch 6) after fatigue-stressing in the Haigh machine in axial tension ranging from 27,000 to 127,000 pounds per square inch for various numbers of cycles. Each point represents one test specimen.

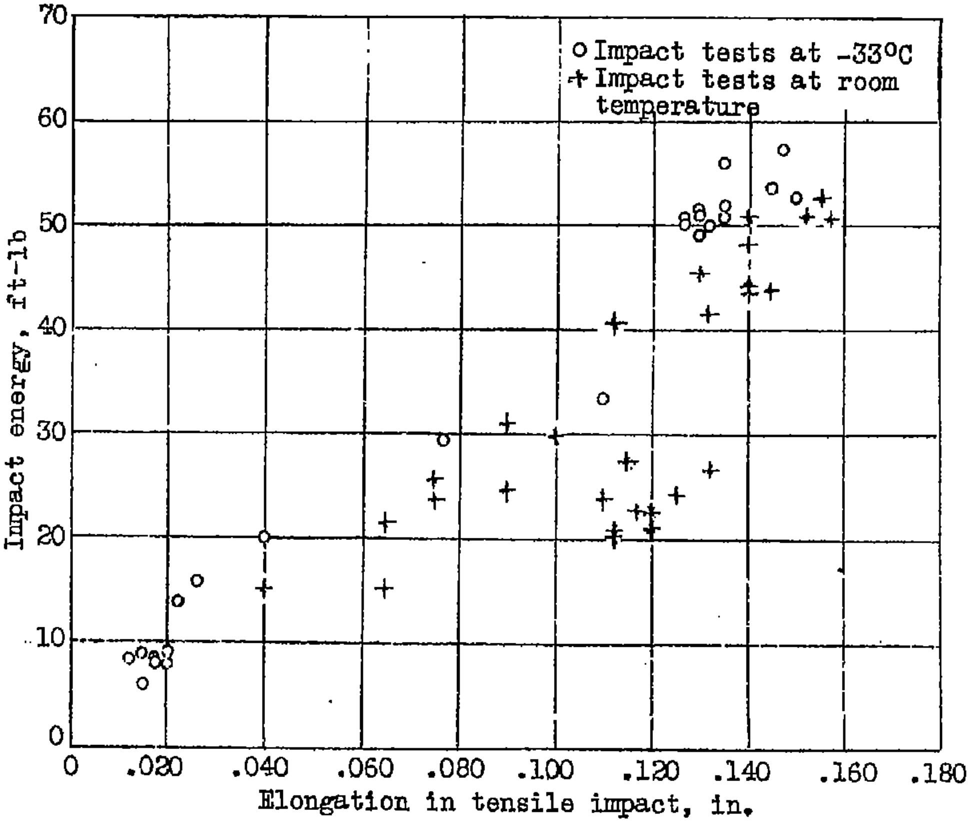


Figure 14.- Relationship between impact energy and elongation in tensile impact tests of specimens of normalized S.A.E. X4130 steel (batch 6) after fatigue-stressing under axial loading in the Haigh machine.

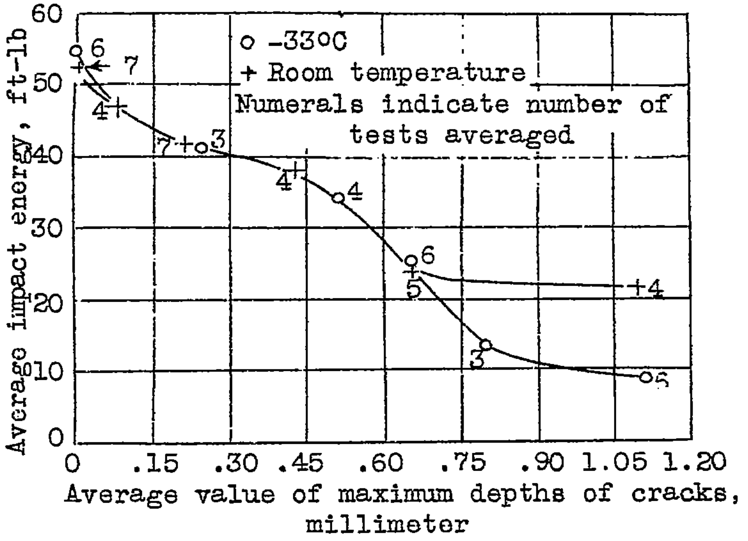


Figure 15.- Variation of average tensile impact energy with average maximum depth of the fatigue crack in fatigued specimens of normalized S.A.E. X4130 steel (batches 3,6, and 9) fatigue-stressed under axial loading in the Haigh machine.

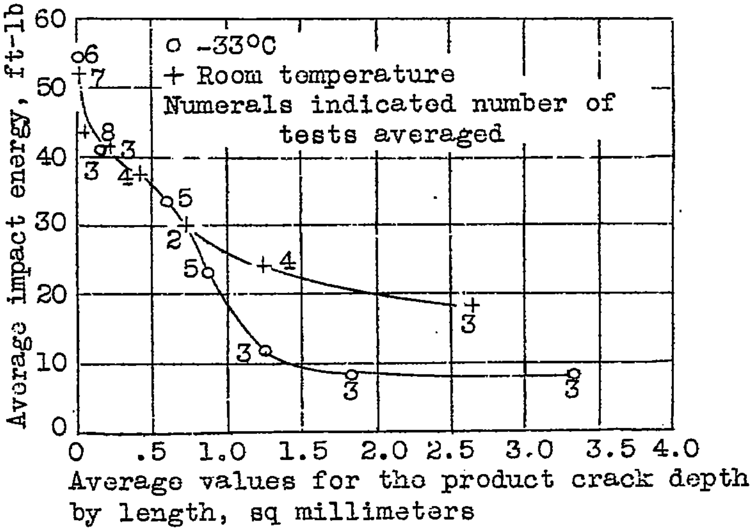
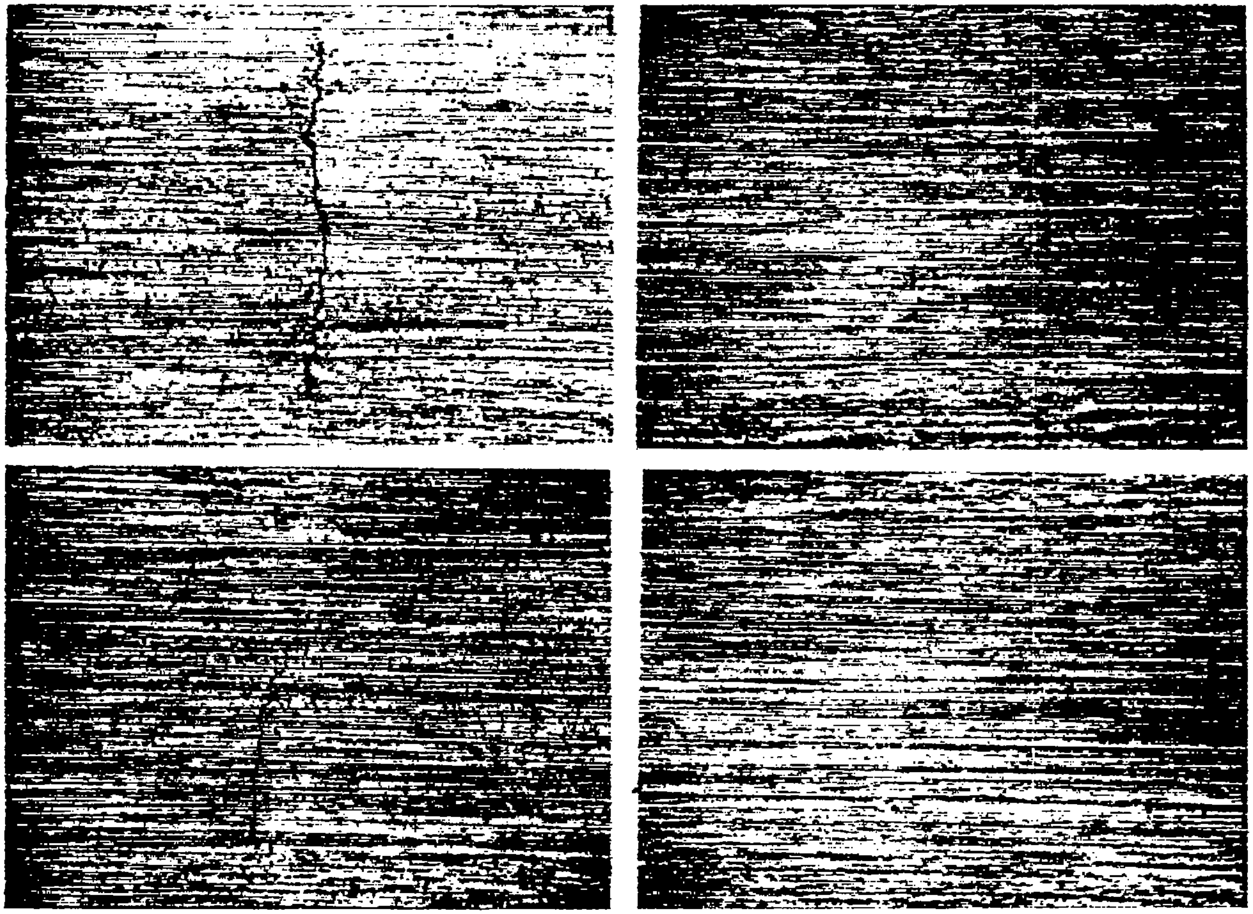


Figure 16.- Variation of average tensile impact energy with approximate crack area in fatigued specimens of normalized S.A.E. X4130 steel (batches 3,6, and 9) fatigue-stressed under axial loading in the Haigh machine.



(a) After repeated stressing in the fatigue machine.

(b) After fatigue cracks removed by machining and surface repolished.

Figure 18.- Fatigue cracks and other surface disturbances in two specimens of normalized S.A.E. x4130 steel. Magnification, 80.

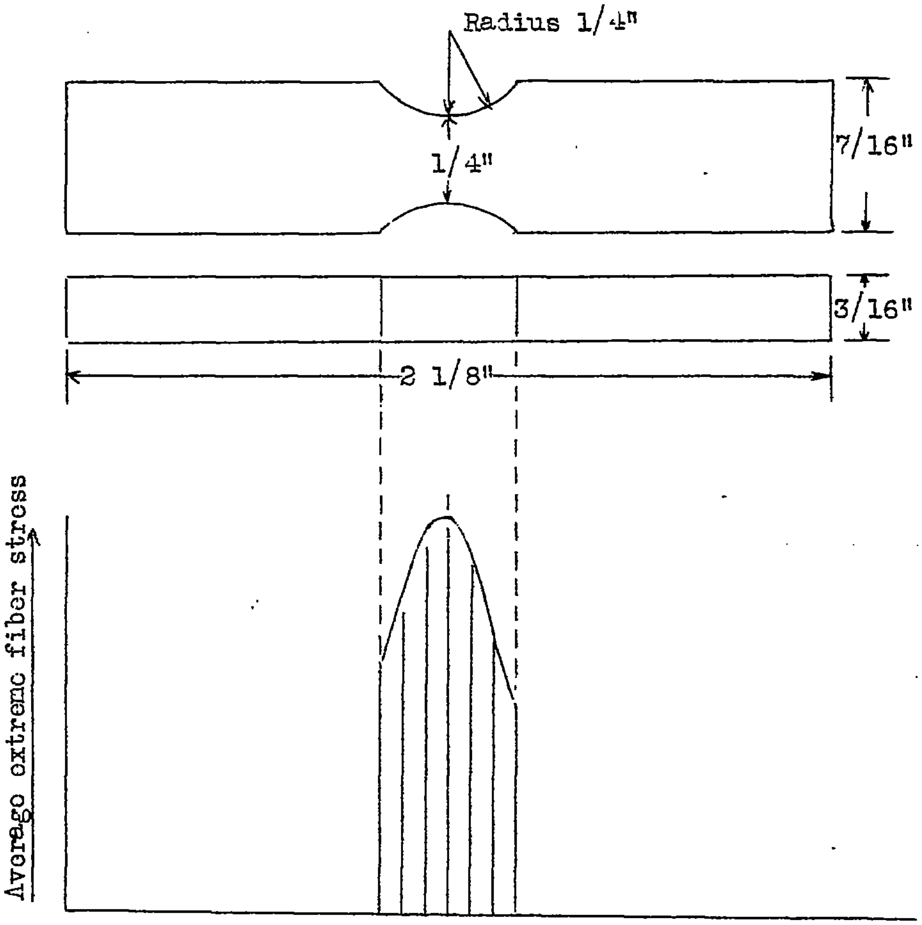
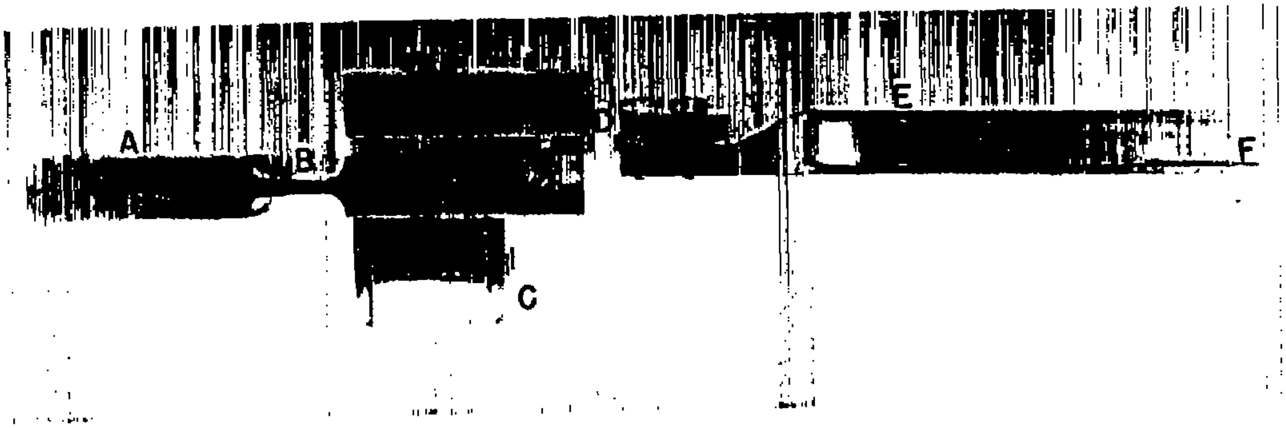


Figure 19.- Flexural fatigue specimen of normalized S.A.E. X4130 steel given repeated stressing in Rayflex machine and variation of average extreme-fiber stress along the part tested.



A rigidly clamped part
B flexible support
C armature
D specimen
E loading arm
F indicating needle

Figure 20.- Assembly used in the Rayflex repeated flexural fatigue machine.

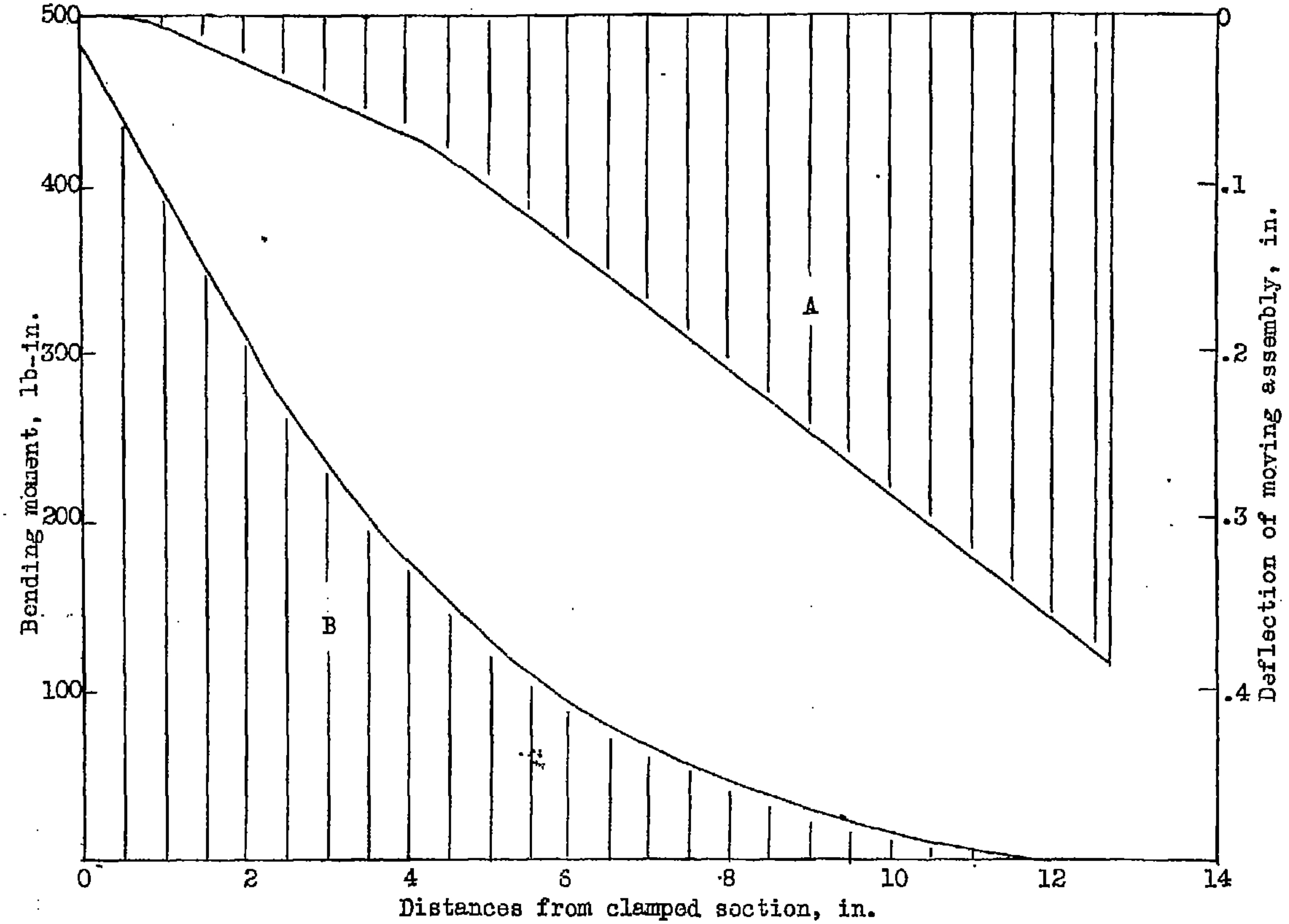


Figure 21.- Distribution of maximum deflections (A) and corresponding bending moments (B) in the vibrating assembly of the Rayflex machine. (Solution by method of reference 27.)

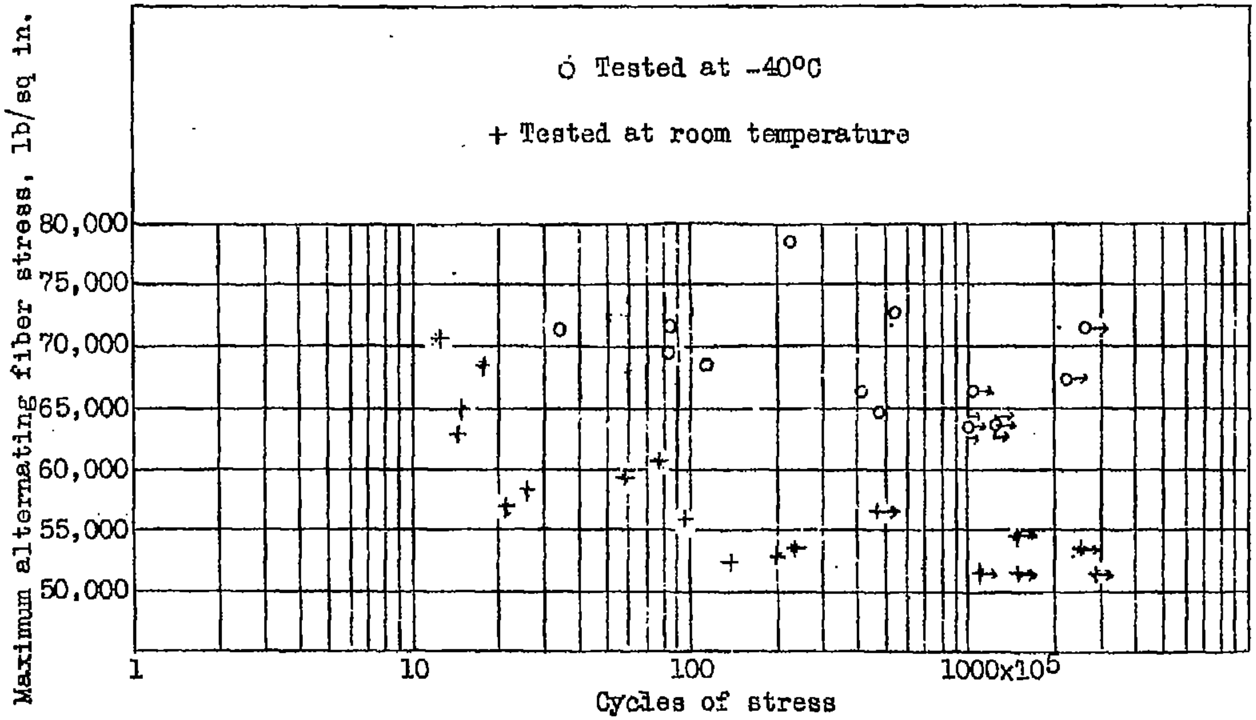


Figure 22.- Fatigue strengths for specimens of normalized S.A.E. X4130 steel tested by repeated flexure in the Rayflex machine at room temperature and at -40°C.

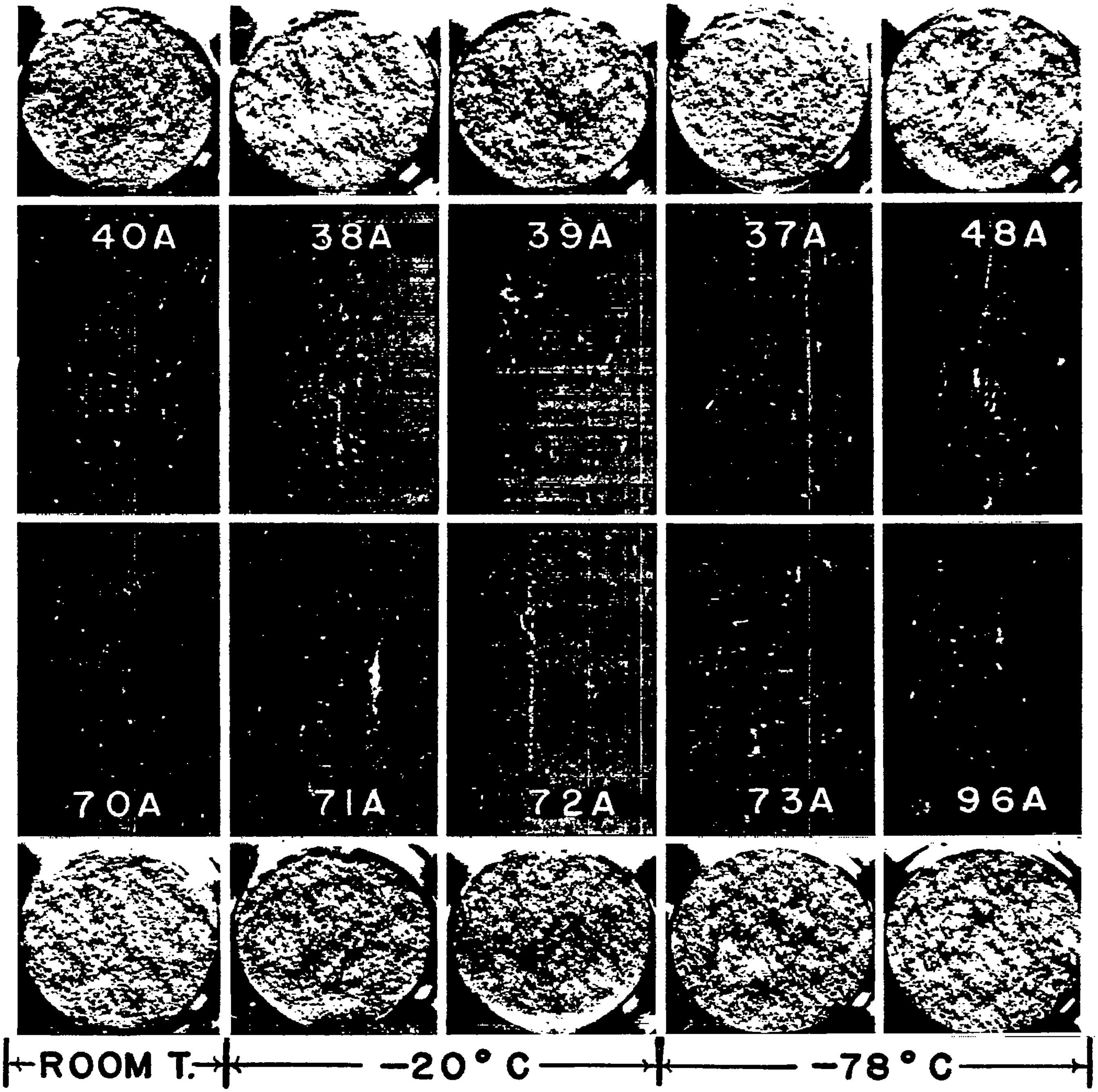


Figure 23.- Notched fatigue specimens of normalized S.A.E. x4130 steel (batch 4) stressed at ±40,000 pounds per square inch as rotating cantilever beams for 50,000 cycles in the Krouse machine.

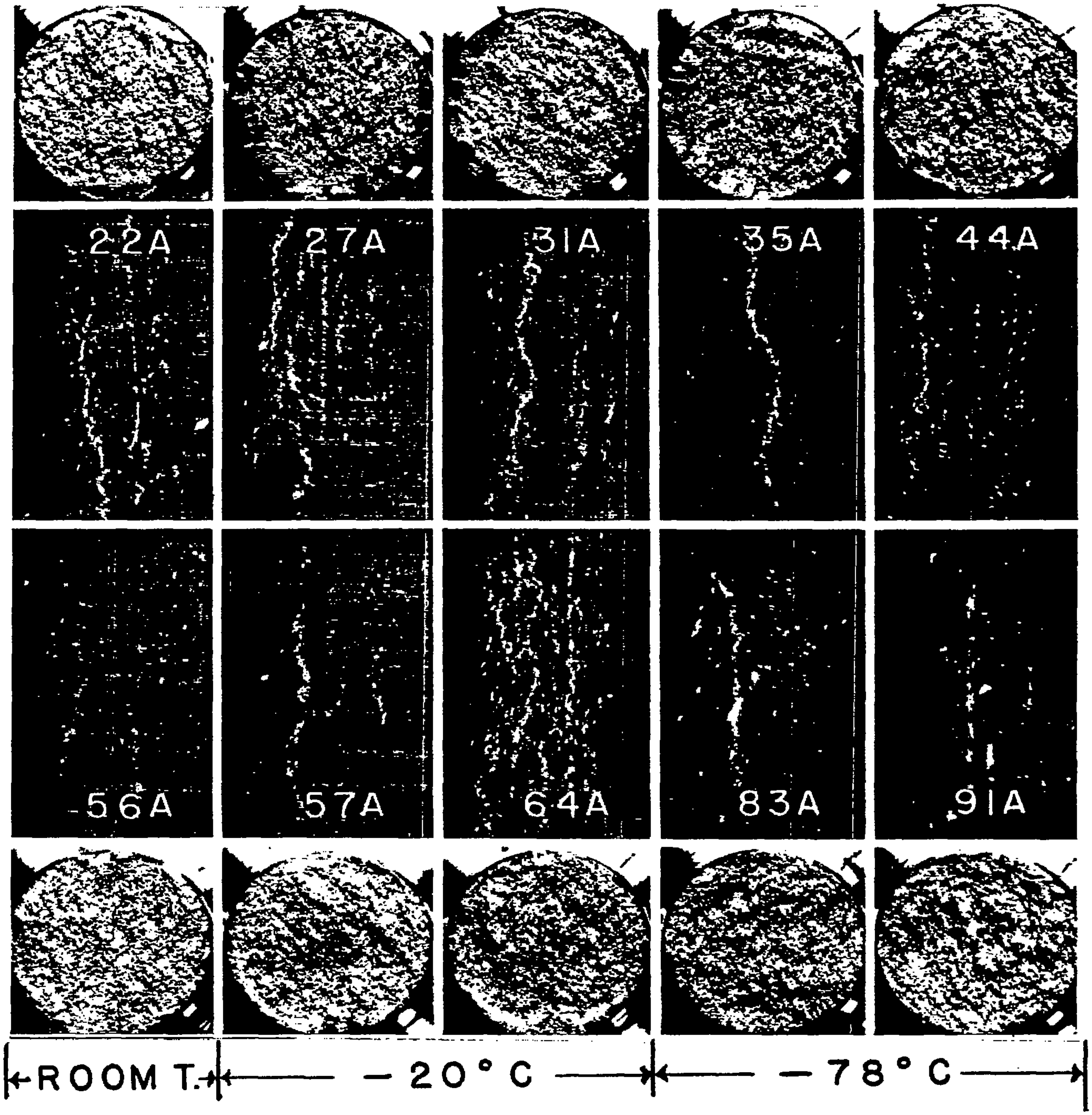


Figure 24.- Notched fatigue specimens of normalized S.A.E. x4130 steel (batch 4) stressed at ±40,000 pounds per square inch as rotating cantilever beams for 400,000 cycles in the Krouse machine.