THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 55, No. 11 JUNE 1, 1939 SECOND SERIES

An X-Ray Study of the Changes that Occur in Malleable Iron During the Process of Fatiguing

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(Received April 17, 1939)

Carefully prepared test bars of malleable iron have been fatigued; x-ray diffraction patterns were taken of each specimen at intervals as fatiguing progressed. This study shows that, when malleable iron is fatigued below its endurance limit, no changes in internal structure that are detectable by the camera used occur after the first few cycles. However, when malleable iron is fatigued above its endurance limit, marked changes do occur. Appreciable changes may occur during the first few cycles of fatiguing. Changes then take place comparatively slowly during the major part of the fatiguing process. These changes proceed at an accelerated rate as the specimen approaches failure. The changes consist of (1) rotation of some of the grains, (2) introduction of strains in some of them, and (3) fragmentation of some of the grains into sizes small enough so that they arrange themselves with random orientation. These changes are all readily detectable with the camera used.

INTRODUCTION

IT is highly desirable, from a theoretical as well as a practical point of view, to know just what changes in structure occur in metals during the process of fatiguing. If changes in internal structure do occur, it is important to know whether they take place only when the metal is fatigued at a stress above its endurance limit or at all values of the fatiguing stress. Since x-rays are one of the best tools that scientists have at their disposal with which to study internal structure of matter, it is natural to attempt to use them to study fatigue. During the last three years, the author has been working on the problem and is of the opinion that very useful information can be obtained by taking diffraction patterns of metals at intervals as fatiguing progresses. Studies of several different metals have been made and some of the results are sufficiently conclusive to report in detail at this time. This paper will be confined to the results obtained by studying malleable iron. Results pertaining to other metals will be reported at a later date.

Some of the earliest experiments in this field were performed by Dehlinger,[1] who investigated the changes produced in cold-rolled copper and silver sheets by repeated bending. Barrett[2] has given a critical review of the literature up to 1936, including a rather complete bibliography. During the last few years Gough and Wood,[3,4] and Barrett[2,5] have done careful and extensive

[1] U. Dehlinger, Naturwiss. **17**, 545 (1929).
[2] Charles S. Barrett, "The Application of X-ray Diffraction to the Study of Fatigue in Metals," Am. Soc. for Metals, Preprint, October, 1936.
[3] H. J. Gough and W. A. Wood, Proc, Roy. Soc. **A154**, 510–539 (1936).
[4] H. J. Gough and W. A. Wood, Proc. Roy. Soc. **A165**, 358–371 (1938).
[5] C. S. Barrett, *Metals and Alloys*, **8**, 13–21 (1937).

work and reported their findings. Unfortunately, the results of these workers are in sufficient disagreement to lead to quite different conclusions.

Preparation and Fatiguing of the Specimens

Samples of properly annealed malleable iron were used. (An x-ray diffraction pattern will reveal conclusively whether or not malleable iron is properly annealed.) Each specimen was machined to one-half-inch diameter. A constriction of circular contour was then machined near one end, the smallest diameter of this constriction being $\frac{3}{8}$ of an inch. The last half-dozen cuts with the lathe tool while machining the constriction were each about 0.001 of an inch deep. The specimen was then polished with fine aloxite cloth. Finally, the specimen was etched with acid to remove any metal that might have become strained during the machining and to remove the finely powdered iron and abrasive dust which had become imbedded in the surface of the metal. With this type of surface, the specimen has a lower fatigue limit than it would have if it had been polished and not etched. However, crystallites which have been broken up by machining and polishing and those which have had strains introduced in them must be removed from the sample or the results will be confusing. A study of such a surface should reveal what changes occur due to the repeated stresses of fatiguing not confused with strains that have been produced by other processes before fatiguing has started.

The specimens were fatigued in an ordinary rotating beam machine in my laboratory. They were removed from the machine at intervals as fatiguing progressed and diffraction patterns taken of them.

The Camera

The main part of the camera consists of a casting into which two one-half-inch holes, spaced three inches apart, were bored to receive and hold the specimen. The specimen and camera were marked so that the specimen could be removed and replaced in the camera in exactly the same position. Thus, the x-ray beam impinged upon the same part of the specimen each time an exposure was made. An ordinary collimator which produced a beam of circular cross section was affixed to the casting. The x-ray beam struck the specimen near the middle of the constriction at a point on its smallest circumference or at a point which was subjected to the maximum stress. However, it must be admitted that the x-ray beam did not necessarily strike the point where the maximum strain occurred or where the first fatigue crack would start. It is obvious that, because of the slightly nonhomogeneous structure of the specimen, the greatest strain may occur at any point on the smallest circumference, and not necessarily in the area surveyed by the x-ray beam. A flat film was placed so as to receive the rays diffracted from the 211 planes in a direction nearly perpendicular to the film. This arrangement made the camera quite fast. The films shown in this paper were exposed 30 minutes. The $K\alpha$ line from an iron target was used.

Results

Figure 1(A) is the pattern from specimen No. 1, which has been subjected to 1000 cycles of fatigue at a stress just under the endurance limit. Fig. 1(B) is a pattern from the same specimen after it had been subjected to 10,000,000 more cycles of fatigue under the same conditions.

Figure 2(A) is the pattern from specimen No. 2 before fatiguing was started. Fig. 2(B) is the pattern from the same sample after it had been subjected to 1000 cycles at a stress slightly greater than the endurance limit. Fig. 2(C) is the pattern from the same specimen after 500,000 cycles, Fig. 2(D) after 2,000,000 cycles, and Fig. 2(E) after 2,300,000 cycles. The specimen broke after 2,500,000 cycles. Fig. 2(F) is the pattern from the broken end of the specimen.

Figure 3(A) is the pattern from specimen No. 3 after it had been subjected to 1000 cycles of fatigue at a stress greater than the stress applied to specimen No. 2. Fig. 3(B) is the pattern from the same specimen after 500,000 cycles, Fig. 3(C) after 750,000 cycles, Fig. 3(D) after 1,000,000 cycles and Fig. 3(E) after 1,200,000 cycles. The specimen broke after 1,300,000 cycles. Fig. 3(F) is the pattern taken with the x-ray beam impinging on the broken end.

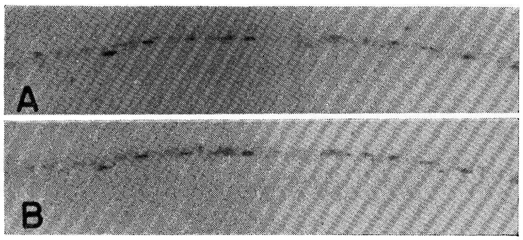

FIG. 1. X-ray pattern from specimen No. 1 after (A) (1000 fatigue cycles) and (B) (10,000,000 additional fatigue cycles). Stress just under endurance limit.

Discussion of the Results

Figure 1(B), taken after 10,000,000 cycles of fatiguing just under the endurance limit for the specimen, is an exact duplicate of Fig. 1(A), taken after 1000 cycles. Each of these two patterns has the same number of spots distributed in the same way. Corresponding spots in the two patterns have the same intensity and structure as nearly as can be seen by the naked eye. Evidently, no changes in the internal structure of malleable iron, which are detectable by this camera, occur after the first few cycles of fatiguing if the specimen is fatigued below the endurance limit. This is in agreement with Gough and Wood's[3] results obtained with mild steel, but in disagreement with the general conclusion drawn by Barrett.[2, 5] Neither Gough and Wood nor Barrett worked with malleable iron.

Figure 2(B), taken from specimen No. 2 after 1000 cycles of fatiguing at a stress slightly above the endurance limit, has several more spots than Fig. 1(B), taken before fatiguing started. One might assume from this that some of the crystallites rotate slightly and some of them break up into smaller units during the first few cycles of fatiguing. This is in agreement with some of Gough and Wood's[3, 4] findings. Fig. 2(C) and Fig. 2(D) are not markedly different from 2(B) or from each other. Fig. 2(E) shows that some of the crystallites have been broken down into small enough fragments to assume nearly random orientation and some of them are severely strained as is indicated respectively by a more marked background in the line and blurring of the spots that remain in the line. A condition like that indicated by Fig. 2(E) always indicates that the specimen is approaching failure very rapidly. Evidently, after the first few cycles of fatiguing, changes take place very slowly during the major part of the fatiguing, but as the specimen approaches failure changes, consisting of the incidence of marked grain distortion and some fragmentation, take place more and more rapidly as the specimen approaches failure. While grain distortion and fragmentation is more marked in some specimens than others, they always precede failure of the specimen. Fig. 2(F) was taken with the x-ray beam impinging upon the broken end of the specimen. It indicates fragmentation of nearly all the grains to a very small size randomly oriented and possessing strains of an undetermined amount.

Gough and Wood[4] state that failure may be preceded by a complete fragmentation of the grains down to a limiting size of 10^{-4} to 10^{-5} cm. with completely random orientation. The writer finds, in the case of malleable iron, that much of this fine fragmentation is associated with the formation of fatigue cracks and with the actual rupture of the specimen. The fine fragmentation indicated in Fig. 2(F) was, of course, produced by the actual breaking of the specimen.

The patterns in Fig. 3 show about the same characteristics as are shown in Fig. 2. The changes took place more rapidly in this specimen because it was stressed more severely. Figs. 3(A), (B) and (C) are not markedly different from each other. Fig. 3(D) indicates marked distortion of the crystallites but very little grain fragmentation. Severe grain distortion as shown by this pattern probably always precedes fine fragmentation. Fig. 2(E) indicates very marked fragmentation of the grains. Fatigue cracks were visible at the time this pattern was taken. Fig. 2(F) again indicates that fragmentation is produced by the process of rupture.

The term "distortion" as used above refers to changes in the grains which causes a blurring of the spots. These changes may consist of an actual bending of atomic planes over an entire grain, the bending of atomic planes over a part of a grain or of "block displacement" of one part of a grain with respect to the other part. It is difficult, and sometimes impossible, to distinguish between these effects by studying a diffraction pattern.

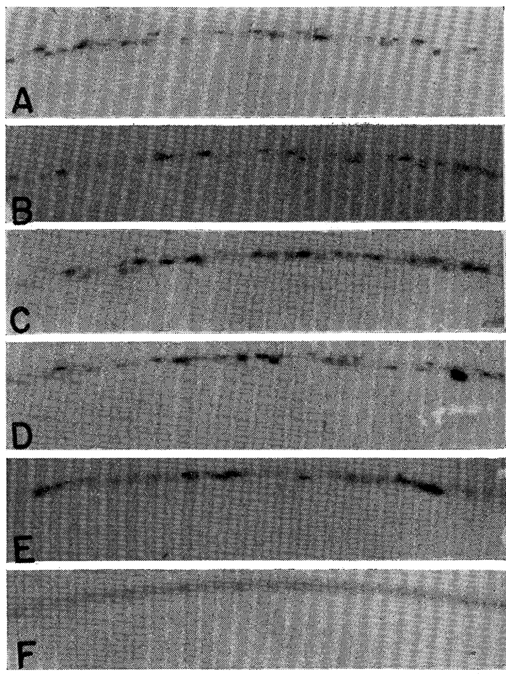

FIG. 2. X-ray pattern from specimen No. 2. Stress just over endurance limit. (A) before fatigue. (B) after 1000 cycles. (C) 500,000. (D) 2,000,000. (E) 2,300,000. (F) from broken end.

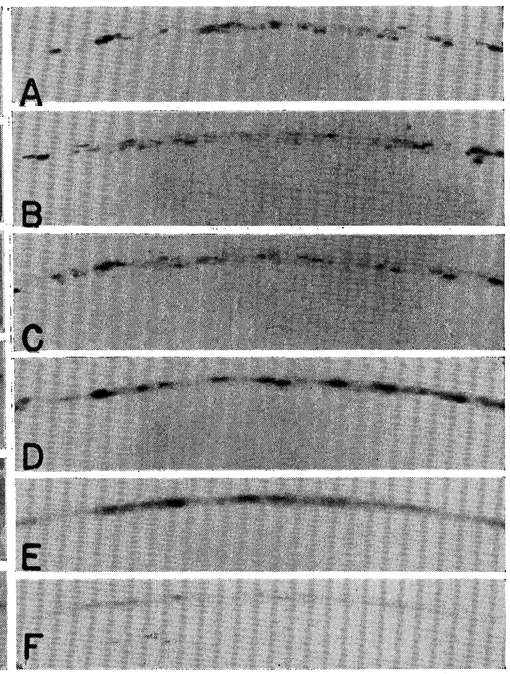

FIG. 3. X-ray pattern from specimen No. 3. Stress greater than that for sample No. 2. (A) after 1000 fatigue cycles. (B) 500,000. (C) 750,000. (D) 1,000,000. (E) 1,200,000. (F) from broken end.

CONCLUSIONS

It appears to be reasonable to draw the following conclusions. (1) When malleable iron is fatigued below its endurance limit no appreciable changes occur in its internal structure after the first few cycles of fatiguing. (2) When it is fatigued at a stress greater than its endurance limit, appreciable rotation of the grains and some splitting of the grains may occur during the first few cycles. (3) Very slight changes in internal structure occur during the major part of the fatiguing process. (4) As the specimen approaches failure very marked grain distortion occurs followed by fragmentation of some of the grains to small enough size to approach random orientation. (5) The formation of fatigue cracks or rupture makes very fine fragments of all the grains adjacent to the fatigue crack or rupture.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge that this study was made possible by grants of money by the Trustees of the Horace H. Rackham and Mary A. Rackham Fund. All of the apparatus, equipment and supplies used were paid for with the money made available by these grants.

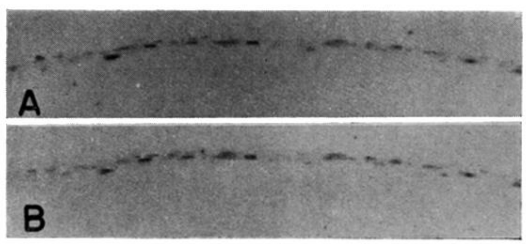

FIG. 1. X-ray pattern from specimen No. 1 after (A) (1000 fatigue cycles) and (B) (10,000,000 additional fatigue cycles). Stress just under endurance limit.

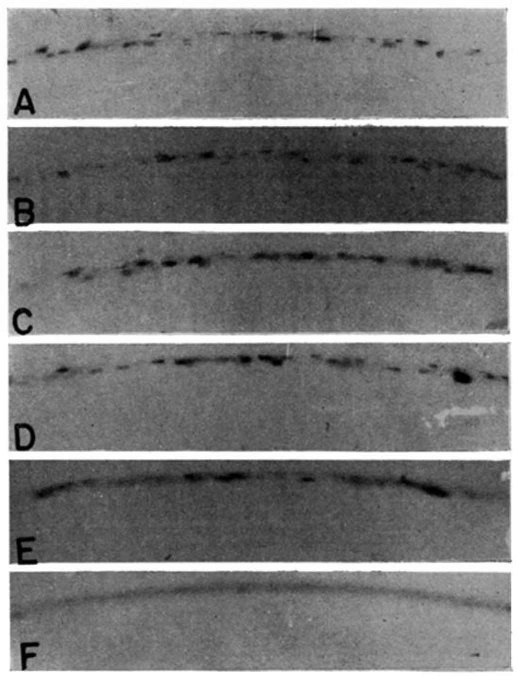

FIG. 2. X-ray pattern from specimen No. 2. Stress just over endurance limit. (A) before fatigue. (B) after 1000 cycles. (C) 500,000. (D) 2,000,000. (E) 2,300,000. (F) from broken end.

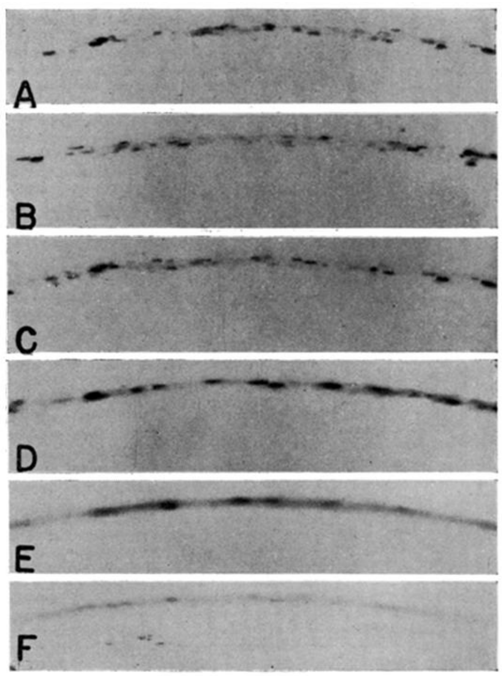

FIG. 3. X-ray pattern from specimen No. 3. Stress greater than that for sample No. 2. (A) after 1000 fatigue cycles. (B) 500,000. (C) 750,000. (D) 1,000,000. (E) 1,200,000. (F) from broken end.