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Repeated Stressing and Crystalline State of Annealed Steel

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Repeated Stressing and Crystalline State of Annealed Steel.

By

Toshio Nishihara and Atsuro Kobayashi.

Abstract.

The action of repeated loading, especially of repeated compression for the crystalline state of 0.41% carbon steel was investigated by X-ray. As a result it was established that the crystal fragmentation occurs when the maximum stress exceeds the lower yield point of that material but has no direct relation with fatigue failure. In the case of alternate tension and compression with equal amplitude (mean stress equals zero), the specimens break down far below the yield point, of course, but is not necessarily preceeded by the crystal fragmentation.

Then, what is the true nature of fatigue of metals is our problem. According to the authors' view, failure begins when the accumulation of crystal distorsion exceeds a certain limit proper to the individual grain.

1. Introduction.

Many reports have already been published about the fatigue of metals, but we can hardly acknowledge that the true nature of it has been investigated throughout, besides, there are some literatures which contradict to each other.

On the other hand, according to the writers' experiment,(1) in the case when two steel rings were rolled on each other compressed with external load crystal fragmentation was observed at the stress where no pitting occurred. Now the principal cause of pitting (Grübchenbildung) is thought to be the fatigue of that material and so it is expected that the crystal break-up will happen below the endurance limit for repeated compression. To ascertain this point directly and to make clear the nature of fatigue of metals the present experiment has been carried out.

2. Experimental Procedure.

As the material was used 0.41% carbon steel the composition of which was denoted in the table 1. The results of static tensile test were showed in the table 2. In most cases test pieces were machined to the dimension as in the figure 1, and after it in order to equalize the quality and to obtain as large grains as possible they were annealed in a vacuum furnace at 860°C during 4 hours.

Testing machine was of Haigh's electromagnetic type and the experiments were performed with three sorts of stress as follows:

i) mean stress is compression,
ii) mean stress is tension,
iii) mean stress is zero.

Stress frequency was 1800 cycles per minute.

After a proper repetition of stresses, test piece being removed from the machine, X-ray photograph was taken from the narrowest portion of it by the back reflection method and was compared with the initial unloaded state. To aim at the same part of the test specimen each time, scratch lines which were marked on it and on the test piece holder were made to coincide at each photographing.

X-ray tube was of sealed hot cathode type and the radiation CoKα was used.

Tube current 3~4 mA, applied voltage 30 KV, and the exposure time was between 5 and 6 hours. Diameters of the first and second slits were 1 mm and the distance between them was about 60 mm (fig. 2).

Table 1.
Composition of the specimens.

C	Si	Mn	P
0.41	0.32	0.48	0.04%

Table 2.
Results of tensile test of annealed 0.41% carbon steel.

Diameter before test	d =14.175 mm
Diameter after test	d' =10.400 „
Elongation	ϕ =36.7%
Contraction	ψ =46.2 „
Breaking stress	σ_T=84.1 kg/mm²
Tensile strength	σ_B=52.7 „
Upper yield point	σ_s =29.5 „
Lower yield point	σ_s' =24.2 „
Young's modulus	E =20370 „

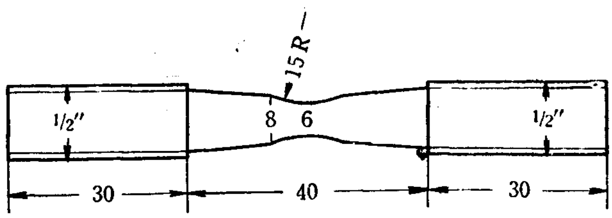

Fig. 1.

(1) not yet published.

Table 3.

Test results of 0.41% carbon steel under repeated stressing.

No. of test piece	Diameter	Stress amplitude σ_a	Mean stress σ_m	No. of repetitions N	X-rayed at	Remarks
	mm	kg/mm²	kg/mm²	× 10⁶	× 10⁶	
H1	6.13	±20	0	5.968	0, 3.0	fractured
H2	6.15	±18	0	12.400	0, 5.3, 7.28, 12.4	not fractured
H3	6.06	±10	−10	9.020	0, 2.06, 4.15, 6.44, 9.02	not fractured
H4	6.10	±18	−18	0.580	0, 0.58	not fractured
H5	6.05	±14	−14	10.860	0, 0.56, 1.346, 3.08, 4.62, 6.42, 10.86	not fractured
H6	6.07	±16	−16	4.000	0, 4.0	not fractured
H7	6.09	±10	−20	0.480	0, 0.48, 1.86	not fractured
H8	6.09	±10	+20	0.240	0, 0.24	not fractured
H11	6.05	±12	−12	13.360	0, 13.36	not fractured
H12	6.07	±20	0	4.160	0, 0.76, 1.3, 3.22, 3.8	fractured
H13	6.08	± 5	−16	11.280	0, 1.97, 6.28, 11.28	not fractured
H14	6.06	±13.5	+13.5	10.080	0, 10.08	not fractured
H51	5.70	±16	+16	4.958	0, 0.19	fractured
H52	5.72	±24	−24	4.940		fractured
H53	5.74	±12	+12	10.050	0, 10.05	not fractured

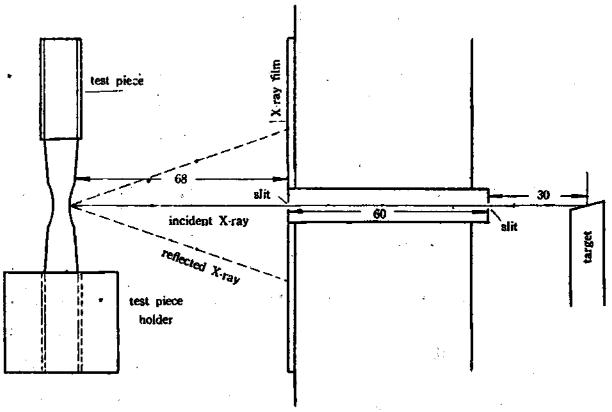

Fig. 2.

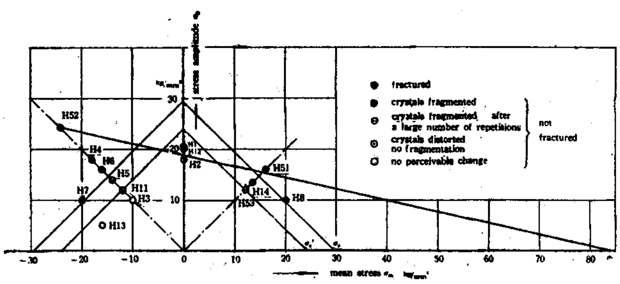

Fig. 3.
Diagram of endurance limit for repeated tension and compression.

3. Results of the experiment.

Experimental results were summarized in the table 3.

Taking the stress amplitude and the mean stress as ordinate and abscissa respectively the diagram of endurance limit will be obtained as in figure 3. Two or three points representing the endurance limits for certain mean stresses and the point corresponding to the breaking stress nearly lie on a straight line.

If the diameter of test piece is too small it yields as soon as it is set in the testing machine and the nuts are fastened as shown in photogrbphs 1 and 2. So in most cases test pieces of 6 mm diameter were used for safety and those of 5.5 mm diameter were employed only at high load.

a) Case when the mean stress is compression.

Static compression test was not carried out, but if it is allowed that the yield point for compression is nearly equal to that of tension, when the maximum stress exceeds the yield point of the material there occurs a marked change on the X-ray photograph. That is, in the case of specimens H4 and H6 after $N=0.58\times10^6$ and $N=1.86\times10^6$ cycles of stress respectively, the interference spots elongated along the circle and formed continuous rings (photo. 3–7). This indicates the crystal fragmentation due to slip and is supposed to occur still more early.

In the case of the specimen H5 which was stressed a little above the lower yield point, similar change occurred after a large number of repetitions (photo. 8–11). Stress a little below the lower yield point was applied to H11 and one can hardly perceive similar change after $N=13.36\times10^6$, but slight blurring seems to appear in many spots (photo. 12–13).

Specimen H3 was stressed still lower than the yield point and after $N=9.02\times10^6$ on the photograph we can read no conspicuous change mentioned above except faint blurring of interference spots (photo. 14–16). Test piece H 7 was subjected to the repeated loading whose amplitude was small but whose maximum value exceeded the yield point of the material and already at $N=0.48\times10^6$ there was noticed a marked change as shown in photo. 18.

After all, a remarkable change such as the crystal smashing happens when the maximum stress goes over the lower yield point of the material, and it was decidedly confirmed by the specimen H13 that the mean stress has no direct relation with crystal break-up. Equal mean stress to H6 was applied to it and at $N=11.28\times10^6$ there was observed no sign of crystal fragmentation. (photo. 19–21).

b) Case when the mean stress is tension.

Specimen H51 was subjected to the stress whose maximum value passes over the yield point for tension. After only $N=0.19\times10^6$ cycles continuation of the interference rings was observed corresponding to the crystal break-up (photo. 22–23) and failure occurred at $N=4.96\times10^6$. Similarly H8 yielded obviously at $N=0.24\times10^6$ (photo. 24–25), but the applied stress lies far below the endurance limit. Maximum stress slightly above the lower yield point was applied to the specimen H14 which showed the yielding of the material at $N=10.08\times10^6$ but not fractured. H53 was tested at $\sigma_a=\pm12\,\text{kg/mm}^2$, $\sigma_m=+12\,\text{kg/mm}^2$, that is, slightly below the yield point, and as the result it showed a faint continuation of interference rings after $N=10.05\times10^6$ still leaving many clear spots on the film (photo. 26–27). In short, at the tension side also, crystal fragmentation happens whenever the maximum stress exceeds the lower yield point and this agrees with Gough's experiment.[2]

c) Case when the mean stress is zero.

According to the above experiments it was ascertained that the crystal fragmentation has no direct relation with fatigue failure.

To inquire into the true nature of fatigue excluding unnecessary conditions is our next problem.

Test piece H 12 was stressed just above the endurance limit and was X-rayed at $N=0.76$, 1.3, 3.22, 3.8×10^6.

Photographs show gradual increase of blurred spots (photo. 28–31). At $N=3.8\times10^6$, that is, 0.36×10^6 cycles before fracture clearness of spots is observed. This indicates the dissolution of lattice distortion in most crystal grains.

To H2 was ayplied the stress below the fatigue limit. After $N=12.4\times10^6$ no marked change is noticeable, but careful observation exposes a slight increase of blurred spots suggesting lattice deformation (photo. 32–35).

4. General Consideration of Results.

The authors reported formerly the experimental research on the fatigue of 0.34% carbon steel subjected to rotary bending.[3] In that case also, clear interference spots decreased gradually before fracture and blurred spots indicating crystal distortion increased as a whole. This agrees with the result of the present experiment, however, whether the crystal distortions decrease or not just befor fracture it was unable to confirm fully owing to grain fineness.

Below the endurance limit also a slight increase of crystal distortion was noticed. And from the present experiment it was established that when the maximum stress exceeds the lower yield point of the material crystal split takes place but at the lower stress it does not. These facts are very important on considering the mechanism of fatigue rupture.

According to Gough and Wood,[4] crystal fragmentation must occur before fatigue failure, however, as Möller's experiment[5] indicates it does not necessarily so.

In the present experiment the specimen H12 which fractured at $N=4.16\times10^6$ showed no sign of continuation of interference rings at $N=3.8\times10^6$. On one side crystal break-up does not necessarily arouse fatigue fracture, on the other side fracture happens without crystal fragmentation. In other words, at least the crystal break-up detectable by X-ray has no direct relation with fatigue failure.

What is the principal factor which governs fatigue phenomenon? From the former and present experiments it is considered to be the crystal distortion.

As Timoshenko, Dehlinger and others state[6], the sort of stress and its magnitude which acts on individual grain constituting the metal material are all remarkably inhomogeneous. Different grains have different shapes, sizes and orientations of slip planes relative to the external force, and from these it is possible that even when one grain produces slipping adjascent grain remains in the range of elastic deformation. Besides the simple elongation, compression or rotation, especially owing to the complexity of grain forms and to the interference of neighbouring grains and perhaps accompanying

(2) H. J. Gough, W. A. Wood, Proc. Inst. Mech. Eng., 141 (1939), 175.
(3) T. Nishihara, A. Kobayashi, Trans. Soc. Mech. Eng. Japan, Vol. 8 (1942), I-194.
(4) H. J. Gough, W. A. Wood, Proc. Roy. Soc., 154 (1936), 510; 165 (1938), 358.
(5) H. Möller, M. Hempel, Mitt. K. W. I. Eisenf., 20 (1938), 15.
(6) Timoshenko, Strength of Materials, II, (1930), 668; U. Dehlinger, Z. Physik, 115 (1940), 625; F. Wever, W. E. Schmid, Mitt. K. W. I. Eisenf., 11 (1929), 114.

with slip itself inhomogeneous lattice deformations such as in torsion or in bending will occur in greater majority and on account of the interferences from neighbouring crystals etc. these deformation does not necessarily die away even if the external load was removed. During the repetitions of stress such lattice deformation reaches a certain limit causing finally crystal bursting. This is not same as an ideal slip and is supposed to generate a sort of weak point, a submicroscopic crack so to speak. And with the occurrence of these submicroscopic cracks here and there, after a certain period there comes the final rupture.

Accordingly, the physical meaning of the endurance limit is interpreted as follows:

Above the endurance limit the number of crystal grains with unrestorable lattice distortion increases gradually, the degree of distortion finally exceeding a certain limit and here the submicroscopic cracks are produced. Then a macroscopic crack will develop rapidly connecting those cracks.

Below the endurance limit, the lattice deformation mentioned above does not exceed a definite limit proper to that crystal or, if not so, very few crystals pass over that limit.

Crystal lattice distortion is unable to detect through the microscopic examination and even by X-ray it is attended by considerable difficulties. Gough states[7] there is no structural change below the endurance limit, however, as he did not compared with the initial state of the same specimen, perhaps the slight change such as crystal distortion was overlooked.

About this point our experimental result agrees with Barrett's experiment.[8]

Möller and others say in their reports[9] that change in the X-ray photograph is very little even above the endurance limit and they do not toutch the problem of crystal distortion. But there is a doubt about the generality of their assertion, for they used 0.02% carbon steel.

5. Summary.

An experimental investigation on annealed 0.41% carbon steel subjected to repeated tension and compression was carried out. As the results the following facts were confirmed:

i) When the maximum stress exceeds the lower yield point of the material crystal fragmentation due to slip occurs producing a remarkable change on the X-ray photopraph. When the maximum stress is below the lower yield point, above mentioned change of crystalline state cannot be observed. Mean stress has no direct relation with this sort of phenomenon.

ii) Crystal fragmentation has no direct relation with fatigue fracture, that is, crystal break-up into smaller crystallites does not necessarily result in fatigue failure, while rupture occurs irrespective of grain size.

iii) Increase of crystal distortion was recognized before fatigue breakdown.

vi) Slight increase of crystal strain was also perceived below the endurance limit, in other words, there is no conspicuous distinction above and below the endurance limit.

Referring the authors' experiment already reported and other literatures the nature of fatigue fracture is considered to be as follows:

a) Owing to the inequality of sort and magnitude of stress for individual grain and accompanying with slip within the crystal, there occurs inhomogeneous lattice deformation such as in torsion or in bending and this does not vanish even if the external force is removed.

b) Under the stresses above the endurance limit such a lattice deformation goes over a certain limit permissible from the grain characteristic generating a submicroscopic crack. Majority of these cracks arouses a macroscopic crack which ultimately leads to fracture.

c) Below the endurance limit the lattice distortion in the individual crystal does not pass over the definite limit or at least very few grains are considered to pass over that limit.

According to the authors' view remaining problem is to demonstrate the growth or the change of crystal distortion directly or indirectly and to explain various facts accompanying fatigue phenomena.

Acknowledgment.

Necessary funds for the pressent research were defrayed from "Hattori Hôkôkai". Also the authors express their gratitude to Dr. K. Kojima for his kind advice.

(7) loc. cit. in (4).

(8) C. S. Barrett, Metals and Alloys, 8 (1937), 13; Trans. A. S. M., 25 (1937), 1115.

(9) loc. cit., also H. Möller, M. Hempel, Z. V. D. I., 83 (1939), 1183; H. Möller, St. u. E., 58 (1938), 499; F. Wever, M. Hempel, H. Möller, Arch. Eisenhüttenw., 11 (1938), 315; F. Wever, Z. V. D. I., 82 (1938), 28; F. Wever, H. Möller, Naturwiss., 25 (1937), 449.

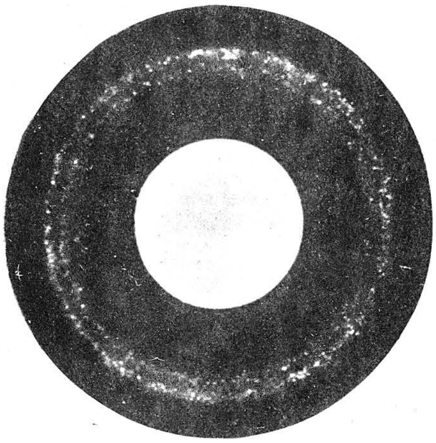

Photo. 1.

Diameter 4 mm, initial state.

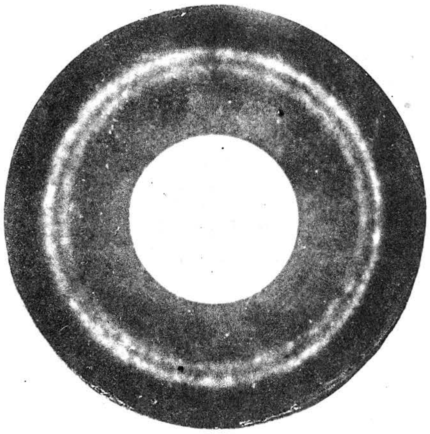

Photo. 4.

Specimen II4,
$\sigma_a = \pm 18$, $\sigma_m = -18$, N=0.58.

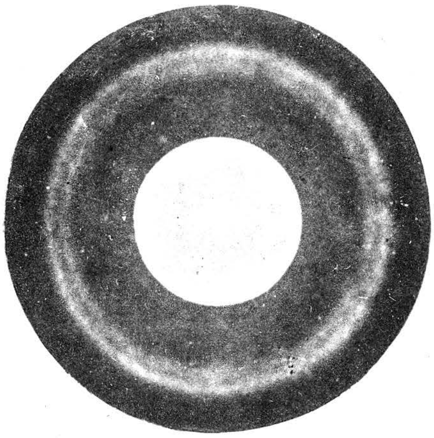

Photo. 2.

Diameter 4 mm,
set in the testing machine and
removed immediately, shows
the yielding of the specimen.

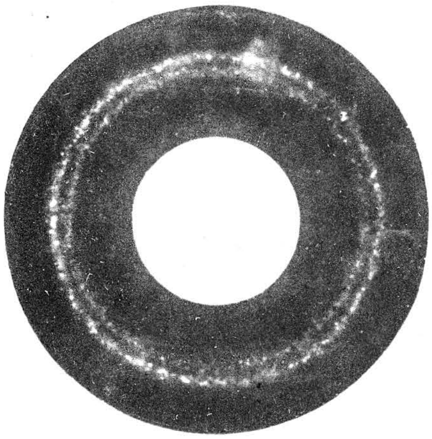

Photo. 5.

Specimen II6, initial state.

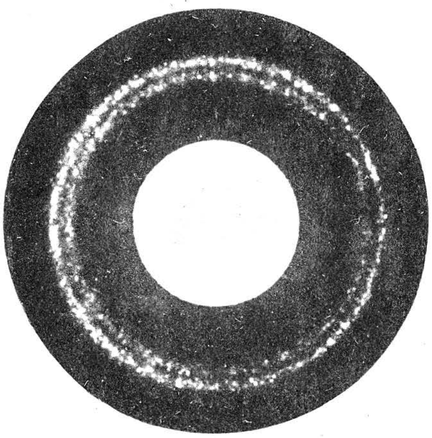

Photo. 3.

Specimen II4, initial state.

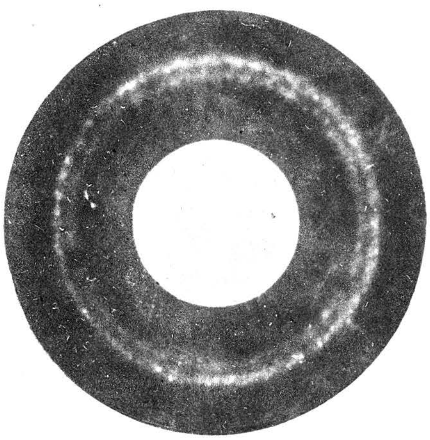

Photo. 6.

Specimem II6,
$\sigma_a = \pm 16$, $\sigma_m = -16$, N=1.86.

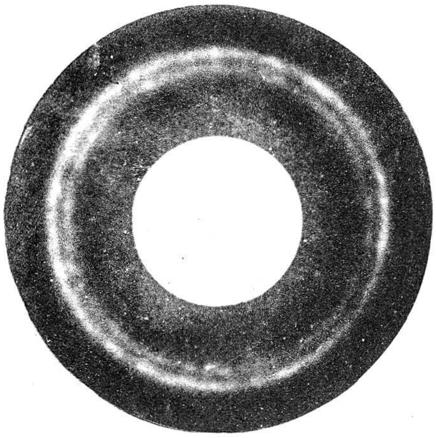

Photo. 7.

Specimen H6,
$\sigma_a=\pm 16$, $\sigma_m=-16$, N=4.

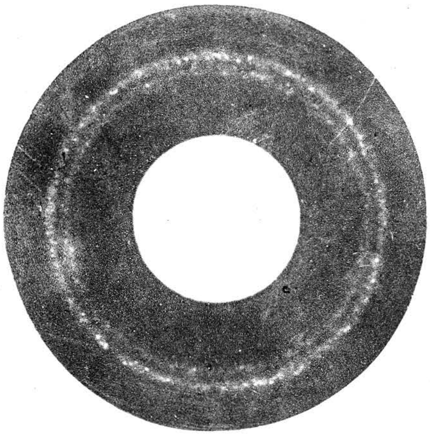

Photo. 8.

Specimen H5, initial state.

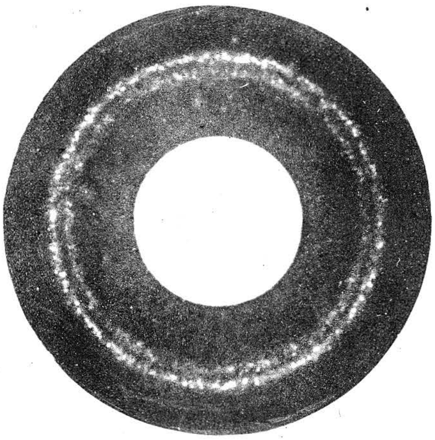

Photo. 9.

Spebimen H5,
$\sigma_a=\pm 14$, $\sigma_m=-14$, N=0.58.

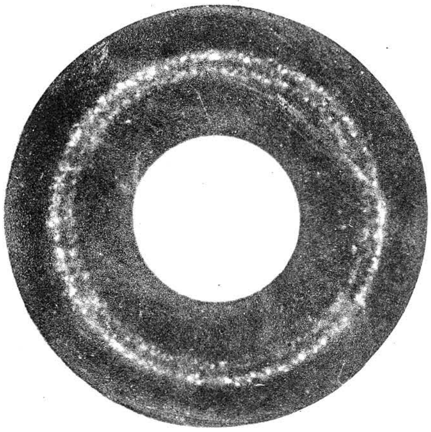

Photo. 10.

Specimen H5,
$\sigma_a=\pm 14$, $\sigma_m=-14$, N=3.08.

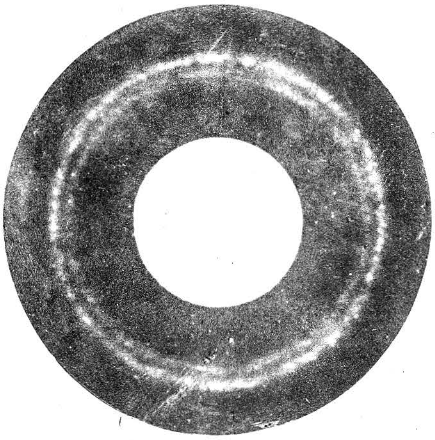

Photo. 11.

Specimen H5,
$\sigma_a=\pm 14$, $\sigma_m=-14$, N=10.86.

Photo. 12.

Specimen H11, initial state.

Photo. 13.

Specimen H11,

$\sigma_a = \pm 12$, $\sigma_m = -12$, N=13.36.

Photo. 14.

Specimen H3, initial state.

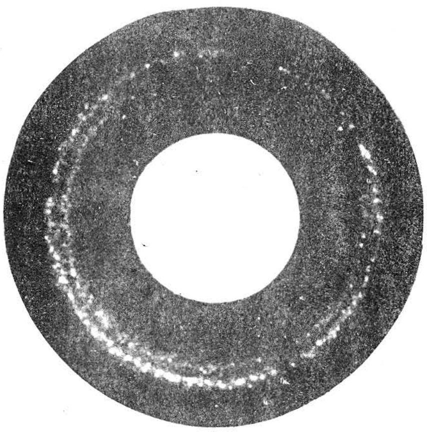

Photo. 15.

Specimen H3,

$\sigma_a = \pm 10$, $\sigma_m = -10$, N=6.44.

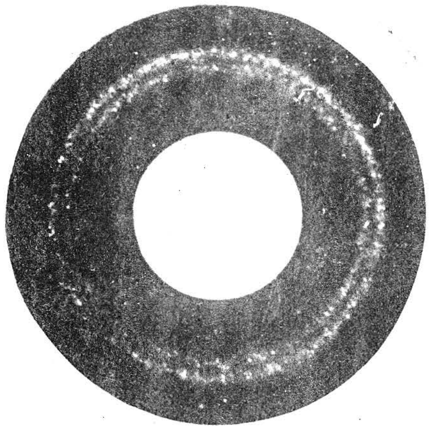

Photo. 16.

Specimen H3,

$\sigma_a = \pm 10$, $\sigma_m = -10$, N=9.02.

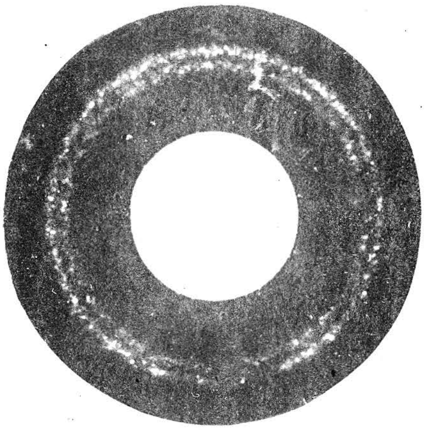

Photo. 17.

Specimen H7, initial state.

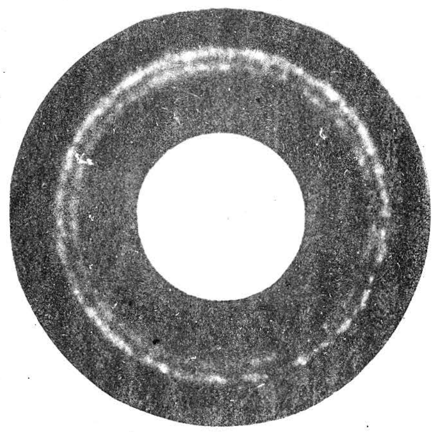

Photo. 18.

Specimen H7,

$\sigma_a = \pm 10$, $\sigma_m = -10$, N=0.48.

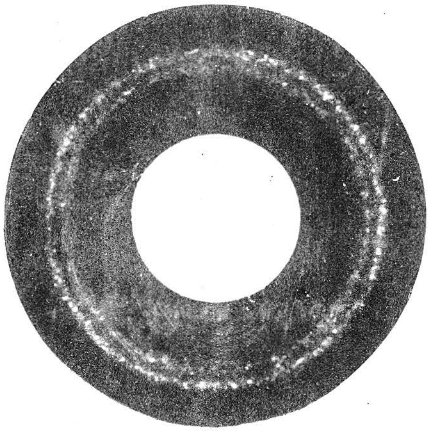

Photo. 19.

Speclmen H13, initial state.

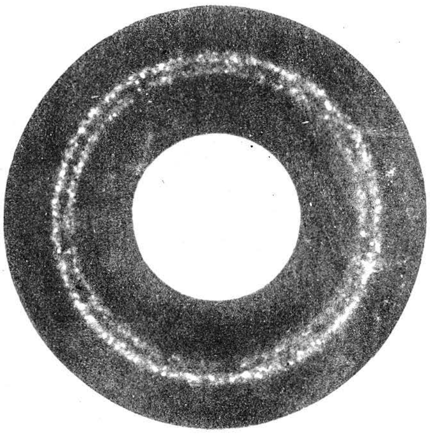

Photo. 20.

Specimen H13,

$\sigma_a=\pm 5$, $\sigma_m=-16$, N=1.97.

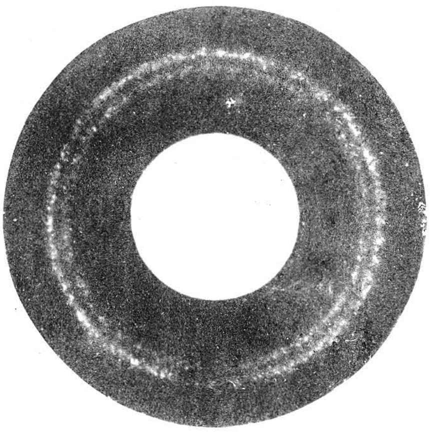

Photo. 21.

Specimen H13,

$\sigma_a=\pm 5$, $\sigma_m=-16$, N=11.28.

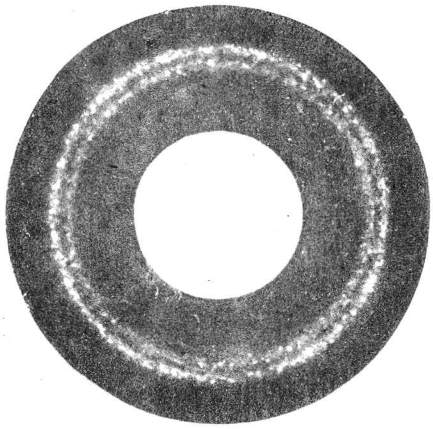

Photo. 22.

Specimen H51, initial state.

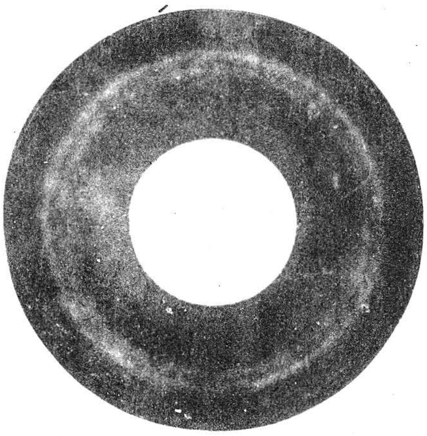

Photo. 23.

Specimen H51,

$\sigma_a=\pm 16$, $\sigma_m=+16$, N=0.19.

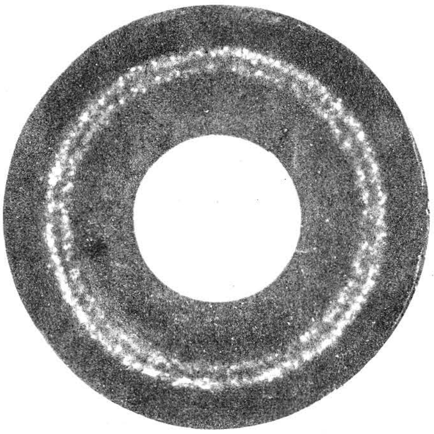

Photo. 24.

Specimen H8, initial state.

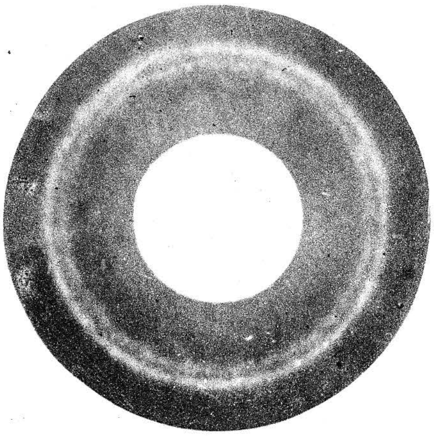

Photo. 25.
Specimen H8,
$\sigma_a = \pm 10$, $\sigma_m = +20$, N=0.54.

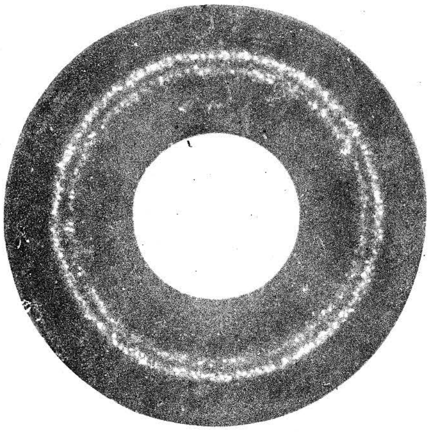

Photo. 28.
Specimen H12, initial state.

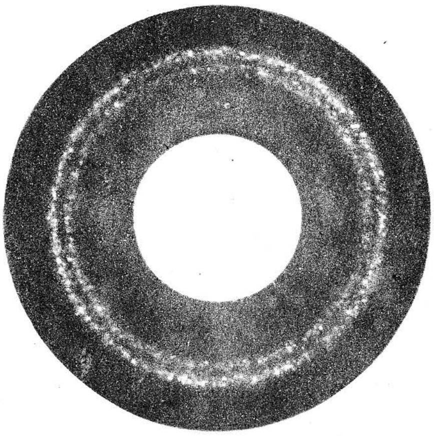

Photo. 26.
Specimen H53, initial state.

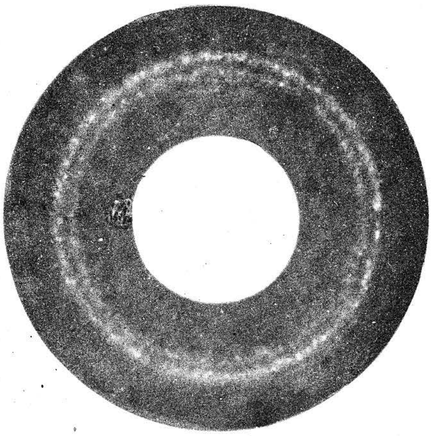

Photo. 29.
Specimen H12,
$\sigma_a = \pm 20$, $\sigma_m = 0$, N=1.3.

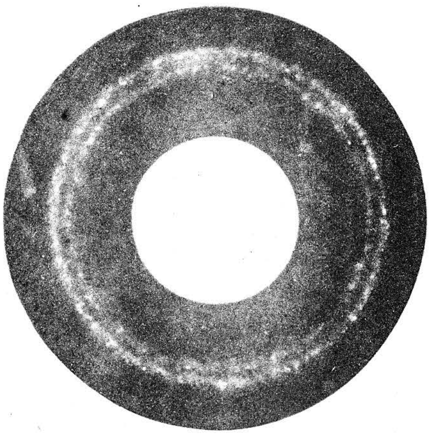

Photo. 27.
Specimen H53,
$\sigma_a = \pm 12$, $\sigma_m = +12$, N=10.05.

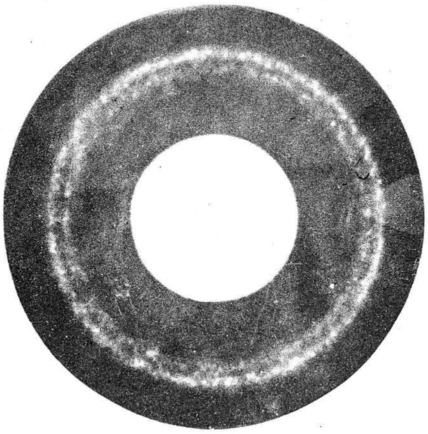

Photo. 30.
Specimen H12,
$\sigma_a = \pm 20$, $\sigma_m = 0$, N=3.22.

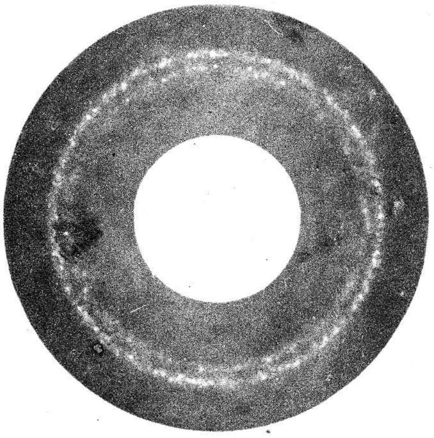

Photo. 31.

Specimen H12,

$\sigma_a = \pm 20$, $\sigma_m = 0$, N=3.8,

clearness of spots noticeable.

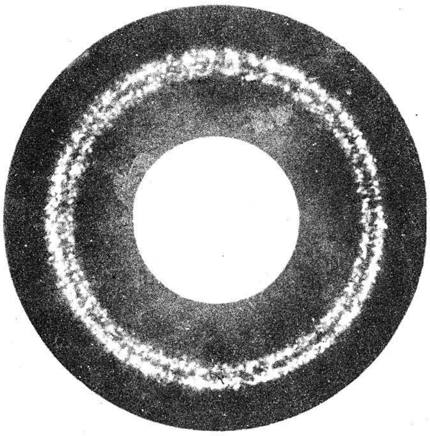

Photo. 32.

Specimen H2, initial state.

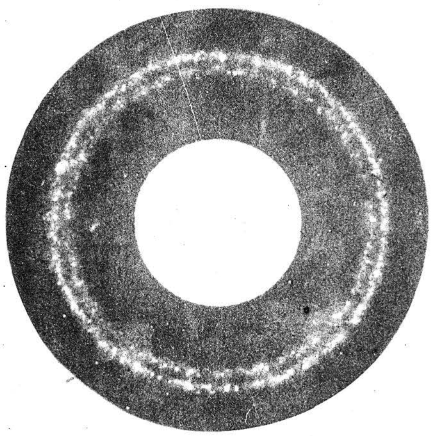

Photo. 33.

Specimen H2,

$\sigma_a = \pm 18$, $\sigma_m = 0$, N=5.3.

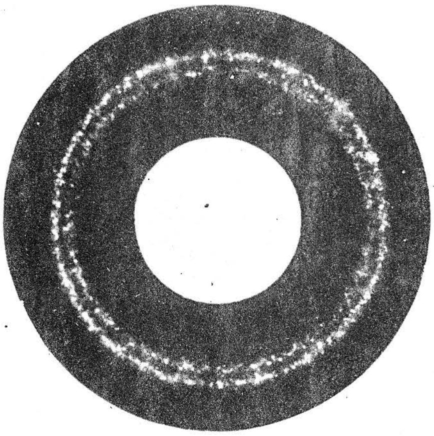

Photo. 34.

Specimen H2,

$\sigma_a = \pm 18$, $\sigma_m = 0$, N=7.28.

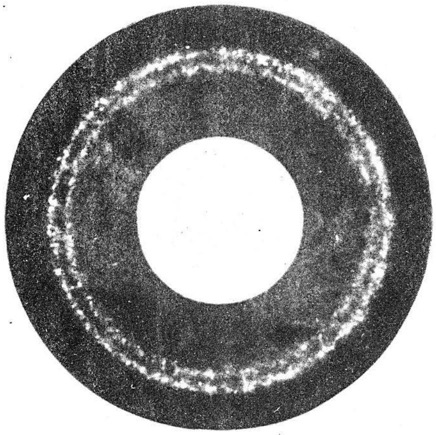

Photo. 35.

Specimen H2,

$\sigma_a = \pm 18$, $\sigma_m = 0$, N=12.4.