CONTRIBUTION TO THE KNOWLEDGE OF PROCEDURES GOING ON DURING CYCLIC STRESSING OF MATERIALS

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SYNOPSIS

The investigations into the behaviour of materials under cyclic stressing consists in the determination of reliable data obtained from endurance tests according to the Woehler method and further clarification of the effects under different stress conditions during cyclic stressing in the material. Besides mechanical methods, electrical, magnetic, X-ray investigation methods, metallographic and chemical-analytical methods are also employed. The changes in microstructure and crystal structure of a mild steel after cold straining and cyclic stressing are discussed in the following.

I. INTRODUCTION

To answer the question, what are the changes taking place in a polycrystalline material under cyclic stressing is a difficult task to be solved in physical and metallurgical research methods.

The theoretical treatment of changes going on in a cyclic stressed material mostly makes use of lattice, energy alternations and atomic processes. These frequently start from two basic assumptions. The first one is, that the stress distribution in a crosssection of a crystal aggregate is not homogenous, but varies considerably from crystal to crystal. The second assumption, which is confirmed to an appreciable extent by microscopical observations[1], is based on the statement, that continuous cyclic deformations result in slip, distortions or dislocations within the crystals due to energy changes.

Theoretical explanations of these procedures become difficult because our knowledge of the behaviour of single crystals under cyclic stressing is incomplete. In particular, it has not been clarified, whether or not the fatigue strengths of single crystals coincide with their yield point, i.e. the stress, at a which noticeable yielding may occur. In polycrystalline materials elastic stresses or distortions of the slip planes which result in strain hardening are introduced in addition to yield and slip effects.[2], [3]. The frequently observed strain hardening of the material at the beginning of a fatigue test is caused by dislocations occurring during slip. A process of dispersion because of reciprocating motion or formation and disappearance of distortions respectively, is connected with strain hardening by slip and is dependent on the magnitude and time of stressing. These fundamental ideas allow of an interpretation of the capacity of strain hardening during cyclic stressing under certain conditions. The fundamental idea of slip, of moving and disapperaring dislocation is, however, insufficient for the interpretation of results at stresses above the fatigue limit, since more accurate ideas about the conditions, which initiate the fracture and the formation of the first crack, are still missing.

Using experimental methods such as mechanical, electrical, magnetic, metallographic and X-ray structure examinations, the alterations in properties under cyclic stressing have been

(1) H.J. Gough, Crystalline structure in Relation to Failure of Metals, especially by Fatigue, Proc. Amer. Soc. Te Test Mat' 33 (1933) II, pp. 3/114.

(2) U. Dehlinger, About the Theory of Fatigue Strength, Z. Phys. 115 (1940), pp. 625/28.

(3) A. Kochendoerfer, Plastic Properties of Crystals and Metallic Materials, issued Berlin 1941, vide pp. 253/78.

repeatedly determined and evaluated. [4,5,6].

For studying the slip procedures under cyclic stressing, materials whose fatigue limits are higher than their yield points have often been used. When, in such materials the cyclic stress exceeds the yield point, strain hardening may result and the strength so obtained would become decisive in determining the fatigue limit. In order to demonstrate the occurrence of such slip processes under cyclic loading materials have to be tested, whose endurance limits are lower than the static yield stress. It was considered possible to reverse the conditions, i.e. at first to induce slip by cold deformation and then to observe the changes in microstructure during a subsequent fatigue test.

II. **PREVIOUS INVESTIGATIONS RESULTS:**

In continuation of the problem of determining the influence of the deformation degree and of the deformation speed on the fatigue strength[7] of cubic body-centered steels (containing 0.02 or 0.4% C respectively) and cubic face-centered steels (18% Cr, 8% Ni and 15% Cr, 27% Ni, 0.35%Ti), the metallographic method was preferred for own investigations, which were carried out in great detail on a mild steel[8], because of its simple and well recognisable microstructure.

In a lecture, at the last annual meeting of the Union of German Metallurgists, some of the earlier results had already been reported[9], where the following indications of metallurgical relationship during formation of the fatigue fracture had been revealed.

If samples made from mild steel were cold strained and cyclic stressed by loads of different amounts and for different periods, practically no changes in the microstructure appeared at stresses below the fatigue limit. When stressing exceeded the fatigue strength ever so little, precipitations were to be observed in the slip planes originating from cold deformation. A strained specimen, which is not cyclic stressed, permits recognition of grain extension and slip lines. However, no precipitates make their appearance.

The microstructre of a sample, prestrained with a high deformation speed of 15,000 % per second, which has cycled under a load of ± 17 tons/sq. in just above the fatigue limit of the cold strained condition up-till fracture occurred (N=2.53 million cycles), is shown as an example in Fig. 1 (at left). In the crystals of the prestrained and cyclic stressed sample black looking and globular precipitations have formed in stringer like arrangement. For the reverse sequence of stresses, i.e. at first cyclic stressing and afterwards cold deformation this phenomenon did not appear. In order to determine the position and the arrangement of the precepitates the microsection was etched with Fry's reagent (Fig. 1 at right). It may be recognised now, that the precipitates had formed only along the slip lines. Hereby the observation is explained why the precipitations are considerably less in samples prestrained to lower deformation degrees compared to those cold strained to higher deformation degrees.

In order to determine the nature of these precipitates, cold strained and cyclic stresses specimens were electrolytically isolated and the residues were examined by X-ray analysis after

(4) F. Koerber, About the Fatigue Fracture of Metallic Materials Dtsch. Akad. Luftahrtforch.. 1939, J. 15.

(5) F. Koerber, The Behaviour of Metallic Materials in the Range of Low Deformations, Stahl und Eisen 59 (1939), pp. 618/26.

(6) H. Karius, Contribution to the question of changes in the material during cyclic stressing, Metallwirtsch. 23 (1944), pp. 419/34.

(7) H.R. Sander and M. Hempel, Tensile and Compression Fatigue Strength and Changes of Properties of Steels after Cold Deformation with different Speed, Arch. Eisenhuttenwesen, 23 (1952), pp. 299/320. Report from Max Plank Institute, Iron Research No. 556.

(8) H.R. Sander and M. Hempel, Metallographical and X-Ray Examination of Soft Iron after Cold and Cyclic Stressing, Arch. Eisenhuttenwes. 23(1952), pp. 383/405. Report from Max Plank Institute. Iron Research No. 557.

(9) M. Hempel, H.R. Sander and H.Moeller, Microstructure and Crystal Stage after Cold and Cyclic Stressing, Stahl und Eisen, 72(1952) pp. 1076/87. Report from Max Plank Institute, Iron Research No. 601.

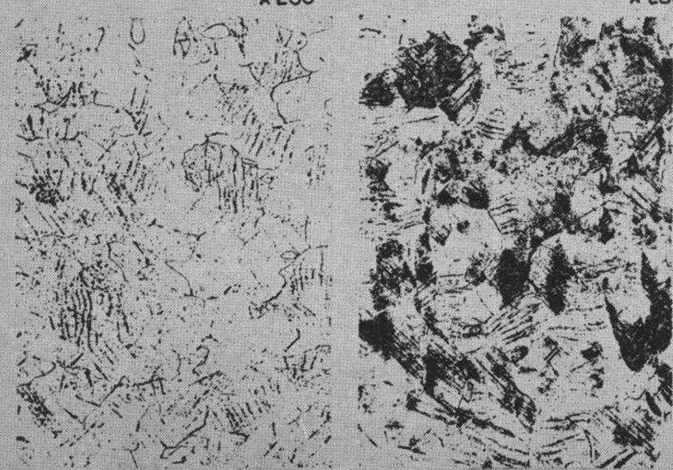


FIG. 1 - APPEARANCE AND ARRANGEMENT OF PRECIPITATES OCCURING IN COLD STRAINED AND CYCLIC STRESSED MILD STEEL.

separation into non-magnetic and magnetic portions. The remarkable result was obtained, that the precepitates occurring in the slip planes of cold strained and cyclic stressed samples of a mild steel consist of the iron carbide Fe_3C (cementite).

These precipitates however do not occur in cold strained and stressed specimens under each and every cylic load. The quantity of precipitates depends on the magnitude and the period of stressing. The relationshops between changes in microstructure and load of stressing are represented in Fig 2. The precipitates are found irrespective of the degree of predeformation and the type of prestraining in the vertically hatched area of the region of finite life. The phenomenon has been interpreted[9] as follows: During tempering of a quenched steel at temperatures above 300° C for comparison cementite should coagulate to a size of a similar order. It is concluded, that during cyclic stressing carbon diffuses to the dislocations at the slip planes and is precipitated there, if the energy introduced corresponds to that of the above mentioned temperature. The precipitates are therefore dependent on a certain and required amount of introduced lattice energy. When the energy is increased excessively, as is in the case of stresses in the upper range of the region of finite life, the dislocations are removed and precipitations do not take place any more. Further support for this interpreation is obtained by investigations[9] into the sharpness of interference rings at cold strained samples, which are cyclic stressed. In the prestrained condition the interference rings are not sharp (vide Fig. 3). If such a sample is cyclic stressed above fatigue limit, the interference rings become sharp again, which indicates, that during stressing, energy is introduced into the lattice to such an extent, that relaxation or even recrystallisation may take place. The temperature level indicated is in a good agreement with that to be derived from precipitation. The relationship between these effects is represented schematically in Fig. 4, which shows, that cementite precipitation slightly precedes the sharpening of the interference rings. This agrees again with the explained indication of a certain temperature energy, since cementite precipitation of this order may occur above 300 deg C., as already mentioned, whilst procedures of relaxation would require temperatures of about 400° C for removal of lattice distortions. It is apparent from Fig. 4 that both the effects may overlap each other. This is further made clear by the experiments, the results of which are represented in Fig. 3 on the right. If a prestrained sample is cyclic stressed immediately in the range of the region of finite life with a load of 16 tons/sq. in, the interference lines become sharp even after about 30,000 cycles. If such a sample, however, is cycled at first under a load corresponding approximately to the fatigue limit and cycling is later continued with ± 16 tons/sq. in. in the region of finite life even upto fracture, the interference rings do not become sharp to the same extent. This may be explained to be due to the fact, that because of the precycling with a lod near the fatigue limit, the precipitates start separating out in the slip planes and stabilise the energy conditions in the slip planes. Consequently crystal relaxation or recrystallisation respectively at these places and at the same time the sharpening of the interference lines is delayed. This effect of precipitations on recrystallisation has been proved already by other observations on metals[10]. The pictures in third and fourth position of Fig. 3 confirm this opinion. The start of precipitations along the slip planes is clearly to be recognised in the sample precycled with a load near the fatigue limit.

III. CYCLIC STRESSING AND HEAT GENERATION:

The results obtained from the experiments described justify the conclusion, that the beginning of the fatigue fracture is related to an energy absorption in the lattice. This energy absorption corresponds to a certain temperature level and is suited to cause place changes of atoms at favourable spots in a similar manner as is the cause at the grain boundaries during creep i.e. during stressing at increased temperatures. If such a irreversible procedure of place change of atoms has once occurred, it is easy to imagine that energy may continue to be stored at such spots until rupture of the material and crack formation is initiated. In order to pursue these ideas, it was provided to make exact temperature measurements of cyclic stressed samples and perhaps to utilise transformation procedures etc. Later for estimating energy or temperature

(10) E. Houdremont, Special Steels, issued Berlin 1943, p. 865 As referred, strongly cold rolled and copper alloyed steels showed indications of disturbances in recrystallisation caused by precipitated foreign cores and this to such an es-extent, that small quantities of precipitated copper are able to prevent recrystallisation.

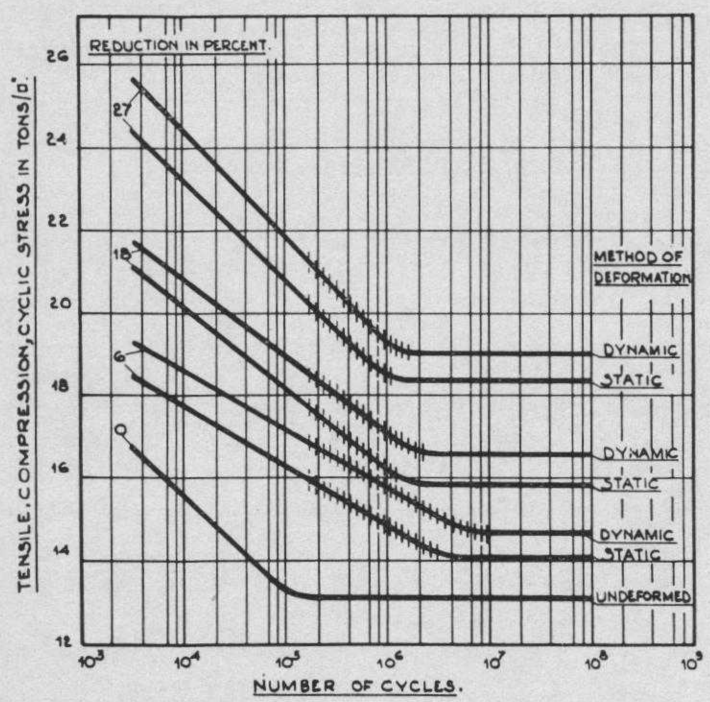


FIG. 2 - RANGE OF PRECIPITATIONS (HATCHED) IN THE REGION OF FINITE LIFE FOR COLD REDUCED AND CYCLIC STRESSED TEST PIECES MADE FROM MILD STEEL.

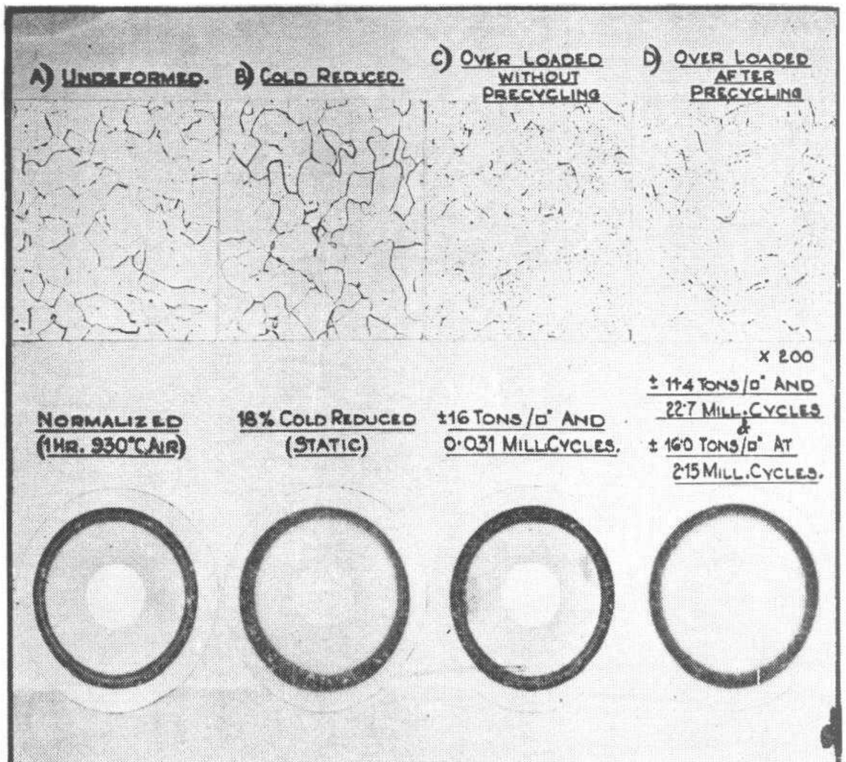


Fig.3 - Relationship between structural changes and alterations of the intensity of interference rings of cold reduced and cyclic stressed test pieces made from mild steel.

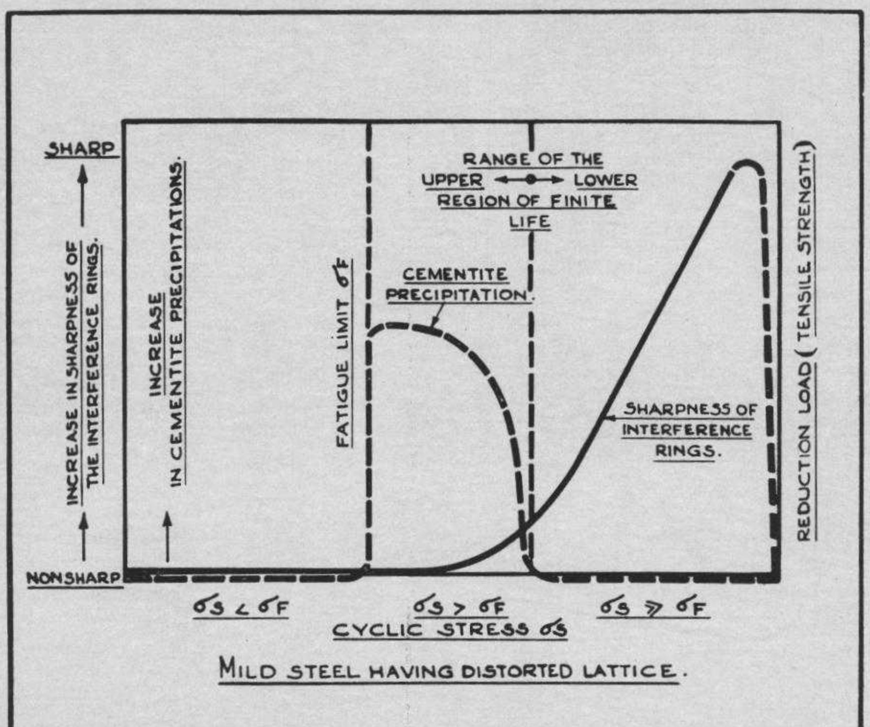


FIG. 4-INFLUENCE OF LOAD DURING CYCLIC STRESSING ON SHARPNESS OF INTERFERENCE LINES AND PRECIPITATIONS AT COLD REDUCED MILD STEEL (SCHEMATICALLY)

respectively during the process of crack formation. The results of such temperature measurements will be reported in the following.

During cyclic stressing an un-alloyed steel with a load in the region of finite life, increase in temperature occurred in a certain range of cycles as may be seen from Fig. 5. In spite of different frequencies, the commencement of temperature rise is rather close, which means, that damage begins at a similar number of load cycles and is not appreciably influenced by the frequency. Further rise in temperature was of course dependent on frequency. The total rise in temperature is less in cooled samples. It should be mentioned, even now that measurements of temperature of the whole sample cannot be evaluated at once for determining the local energy at favourable spots in the lattice from which the fracture starts. The steep rise in temperature when fracture starts, may be considered as very characteristic. The horizontal portion of the temperature curve may be explained to indicate an equilibrium between strain hardening strengthening and hardening decrease (recovery).

As to be expected, the rise in temperature is shifted with increasing load in the region of finite life to a lower number of cycles and at the time becomes steeper (vide Fig .6). The general relationship between Woehler line and heat generation should be clearly recognisable from this figure.

If the assumption, that the horizontal portions in the temperature curves are caused by a change from strain hardening to hardening decrease were correct, then a cold strained material should experience different temperature alterations. Actually under such conditions the range of approximately uniform heat generation is missing (Fig.7) and a gradual temperature increase is immediately followed by a verical rise, which is ypical of the fracture range. It is interesting to note from this figure, that the beginning of the temperature increase at the different degrees of load may be found to correspond to the damage line, whilst the vertical rise in temperature coincides approximately with the Woehler line, at which fracture occurs. It is to be assumed, therefore, that the damge line is actually indicating the beginning of the final material destruction.

Generally steels of different tensile strength have also different fatigue limits and the fatigue limit (σ F) increases with increasing tensile strength (σ T), which, as well known, has resulted the approximate relation $\sigma \text{ F} \sim 0 \cdot 5 \times \sigma \text{ T}$ for notch free and at room temperature cyclic stressed samples. This may be explained to be due to the fact that critical movements of atoms caused by the cycling procedures may be initiated only at an introduction of a correspondingly higher energy in steels treated to higher tensile strength because of their higher lattice energy. For steels of higher tensile strength therefore the heat generation under cylic stressing should be expected to take place at correspondingly higher stresses, which is actually the case as shown in Fig. 8. A more accurate idea about the relationships may be obtained, when instead of tensile strength the yield point is aken as the base value. Although the 0·2 limit of tempered steels represents certain figure selected arbitrarily, it should serve to indicate roughly the first slip movements. In the lower portion of Fig.8 the temperature increase is plotted for all steels investigated against the ratio of fatigue stress to yield strength. The course of this curve should clearly indicate the existing dependencies.

IV. CYCLIC STRESSING AT LOW TEMPERATURE:

With the above point in view it is rather simple to explain the effect of low testing temperatures during cyclic stressing. Because of the strong heat conduction at low temperatures a high load is required to cause the corresponding critical conditions. The fatigue limit therefore must be increased with decreasing temperature.[11] Actually the fatigue limit, which is about ± 16 tons/sq. in. at $+20$ deg. C. is raised to about ± 38 tons/sq. in. at -180 deg. C. as may be seen from Fig. 9. Simultaneously the influence of melting points and of the temperatures of recry-

(11) M. Hempel and T. Luce, Behaviour of Steel at Low Temperatures under Tensile and Compression Cyclic Stressing, Mitt. K. Wilh. Inst. Eisenforsch. 23 (1941), pp. 53-79, vide Arch. Eisenhuettenwes. 15(1942,43) pp. 423,30 and Z. VDI 85 (1941) pp. 992,93.

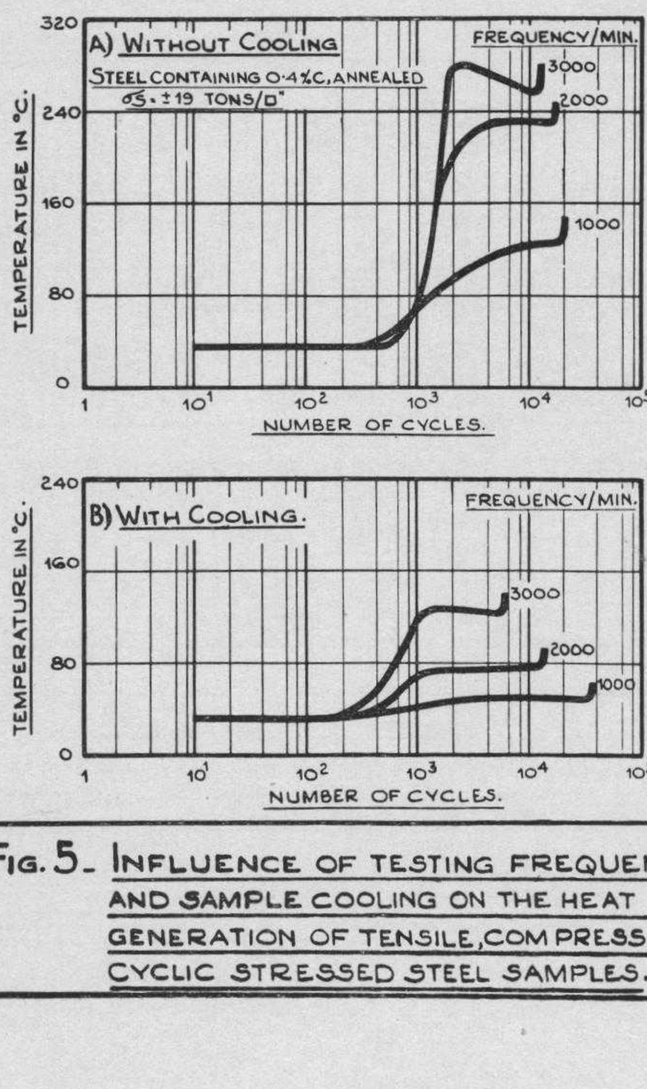


FIG. 5 – INFLUENCE OF TESTING FREQUENCY AND SAMPLE COOLING ON THE HEAT GENERATION OF TENSILE, COMPRESSION CYCLIC STRESSED STEEL SAMPLES.

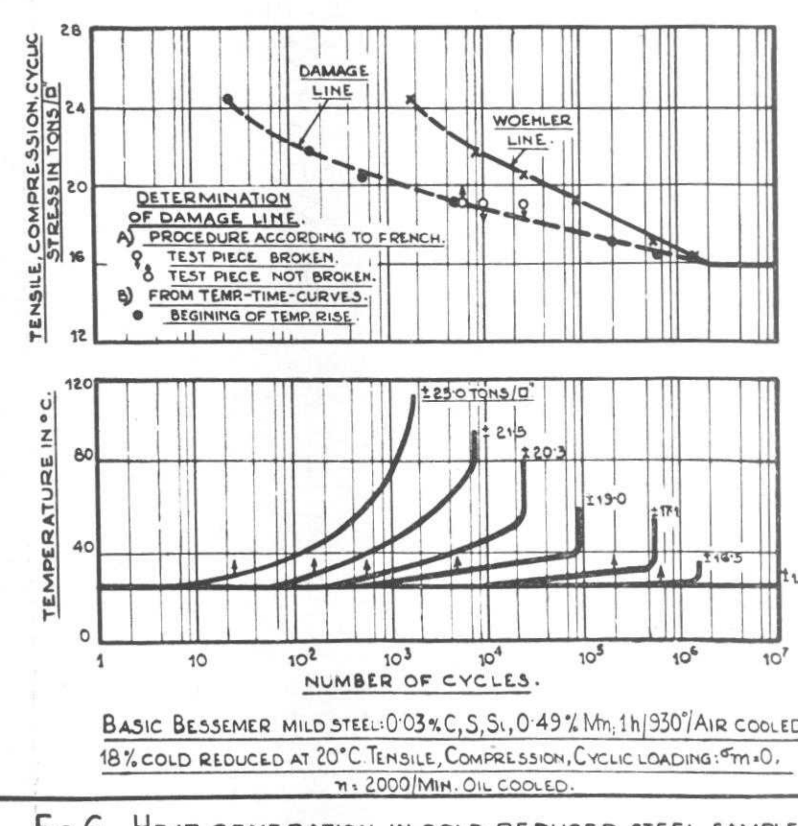
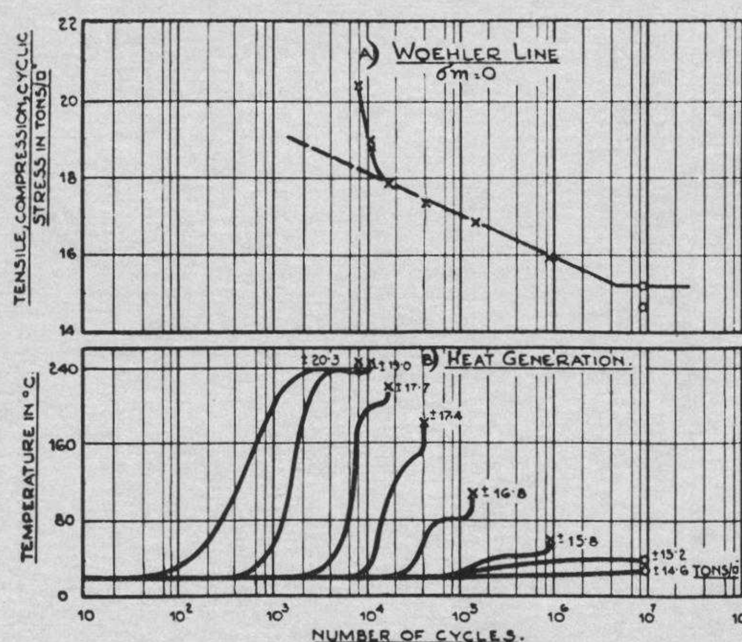


FIG. 6 - HEAT GENERATION IN COLD REDUCED STEEL SAMPLES DURING CYCLIC TENSILE COMPRESSION STRESSING AND ITS RELATION TO WOEHLER AND DAMAGE LINE.



STEEL WITH 0·4 % C, NORMALISED FROM 850°C (2 h), σ0·2 = 25·3 TONS/SQ.IN.
σT = 40 TONS/SQ.IN. TEST PIECE DIA. = 0·3", LEN. = 6", FREQUENCY: n = 2000/MIN.
WITHOUT COOLING.

FIG. 7. INFLUENCE OF LOAD AND PERIOD OF CYCLIC STRESSING ON THE HEAT GENERATION OF STEEL SAMPLES CYCLIC STRESSED BY TENSILE COMPRESSION.

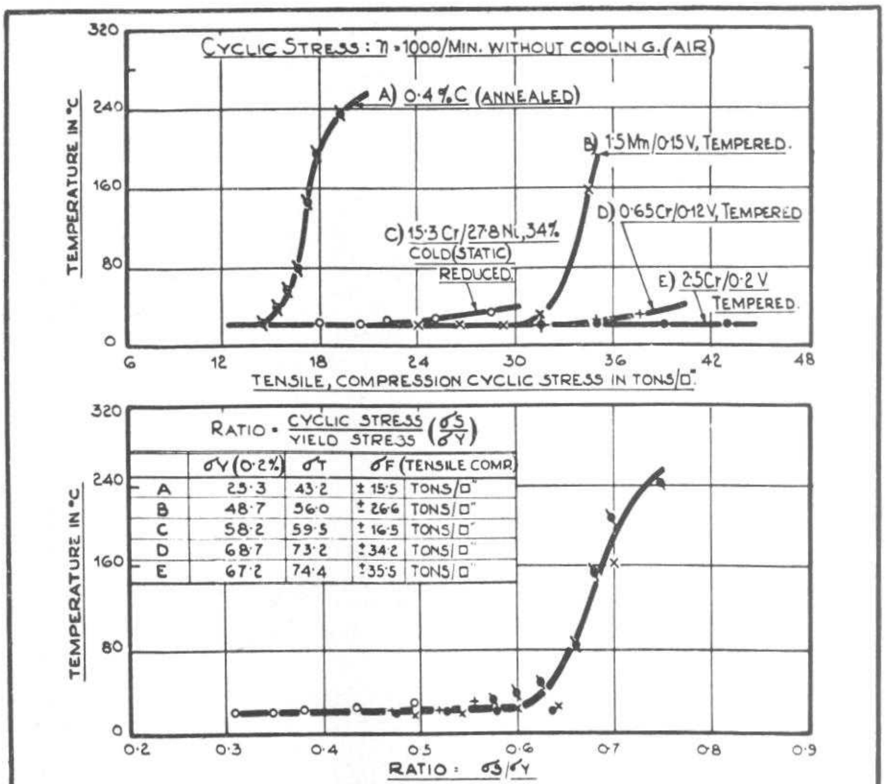
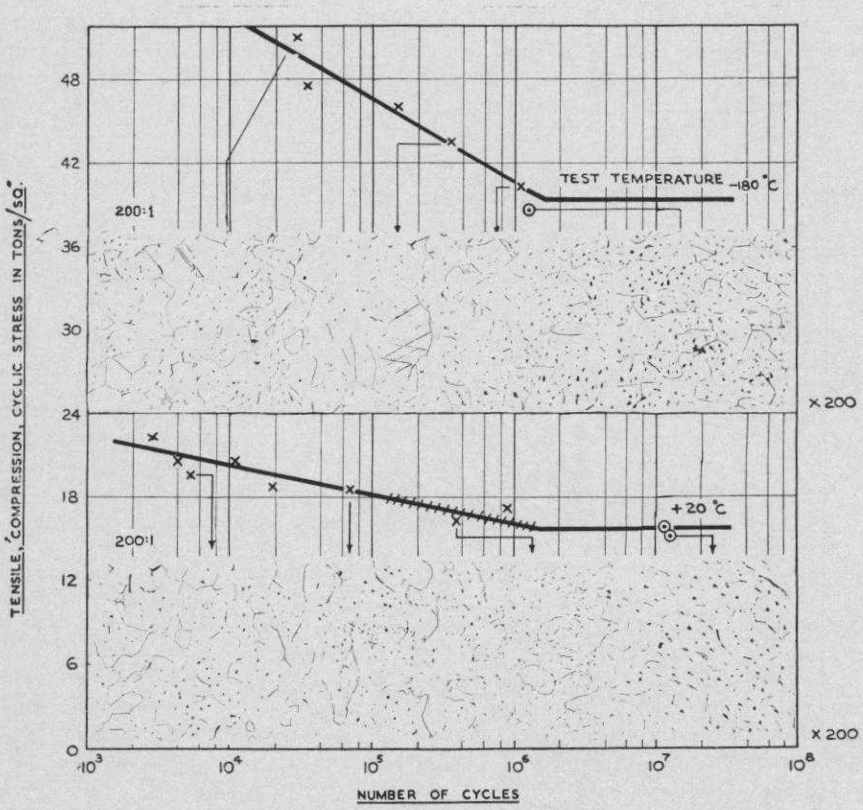


FIG. 8 - HEAT GENERATION IN VARIOUS STEELS UNDER CYCLIC TENSILE, COMPRESSION STRESSING AND ITS RELATION TO THE RATIO OF CYCLIC STRESS TO YIELD STRESS.



MILD STEEL: 18% COLD REDUCED. TENSILE, COMPRESSION, CYCLIC STRESSING: FREQUENCY = 2000/MIN. POSITION OF MICROPHOTO: CORE OF TEST PIECE (0.05" FROM FATIGUE FRACTURE)

FIG. 9. MICROSTRUCTURE CHANGES AND COURSE OF THE WOEHLER LINES FOR MILD STEEL SAMPLES AFTER COLD REDUCTION AT 20 °C AND SUBSEQUENT CYCLIC STRESSING AT +20 °C AND -180 °C.

stallisation of metals, which is dependent on the melting point, on the fatigue limit at room temperature deserves special consideration[12]. It should be particularly interesting to pursue, whether the observed changes in microstructure occurring at room temperature may be found also after testing at low temperatures. As shown in Fig. 9, no visible precipitations appear in prestrained samples tested at -180 deg.C. It is, however, very characteristic, that in the microstructure of samples cycled at low temperatures clear twinning takes place, which indicates, that the slip mechanism of deformation is replaced [8,13] by a twinning mechanism, which usually takes place during brittle fractures under multiaxial stresses at low temperatures or by impact at room temperature. This deviating type of deformation mechanism is further expressed by Fig. 10 showing, that a sample which is precycled at room temperatures and has separated precipitations, does not produce increased quantities of precipitates, but forms twins instead when cycling is continued at low temperature uptil fracture. These results indicate that fatigue testing should be considered further in connection with the deformation mechanism occurring during brittle fractures.

V. FURTHER INFLUENCES ON CHANGES IN MICROSTRUCTURE:

In consequence of these experiments revealing the temperature effects, a few further results will be discussed briefly which have been obtained during investigation into the changes in microstructure at cyclic stressed samples. The influence of the period of stressing on the microstructue after cold straining and cyclic stressing is represented in Fig 11. As to be expected, the quantity of precipitated carbides may be seen to increase with increasing time of stressing. At a similar number of cycles the effect of cycling frequency may be taken from Fig. 12 Omitting the frequency zero, which of course cannot produce changes in microstructure, it is obvious, that the samples tested in the range of frequency from 333 to 3000 cycles per minute have formed precipit tes of a similar order. This means, that probably very slow cycle deformations (for instance $n=10$ cycles per minute) are sufficient, to initiate precipitation in a crystal lattice, distorted by cold work.

It is further of interest, to follow up th existence of precipitates at different distances from the fracture, as it is done in two subsequent figures. According to Fig. 13 maximum precipitation was found at position 1, i.e., next to the fracture and surface. They are noticeable, however, also in the border-zone at places more distant from the fatigue fracture and diminish in quantity towards the core and with increasing distance from the fracture. As may be seen from Fig. 14, no principal change takes place, if the sample size is enlarged. It is noteworthy, that a further crack has started in the sample (1/5" distant from the fatigue fracture) and that also near this second crack the corresponding changes in microstructure may be observed.

The behaviour of precipitates, as expressed in the two last figures, is indicative therefore, that the properties in a border-zone just below the surface and in the core of samples after cold deformation and subsequent cyclic stressing are different. This would mean the stress distribution on the cross section is non-uniform even in samples cycled with tensile and compression stresses. On the contrary, the border-zone is more stressed than the core under such cyclic stressing conditions. Since the precipitations are closely dependent on the slip lines produced by straining, it is to be concluded that the border-zone suffers heavier distortion of the lattice than the material in the core. The deformation takes place a little easier on the surface layer, which may have the thickness of some grains, compared to the core where the deformation is hampered by other grains in the exterior.

VI. CYCLIC STRESSING AT INCREASED TEMPERATURES:

It has been mentioned already, that in the course of fatigue tests conversion of energy (damping, heat generation) may take place and the conclusion was to be drawn that the heat generation caused by cyclic deformation was favouring the precipitation along the slip lines of the

12. Vide A. Kochendoerfer, reference 3.

13. H. Hanemann and A. Schrader, Atlas Metallographicus, Berlin (1933) Vol. I, p. 57 and tables 83.84.

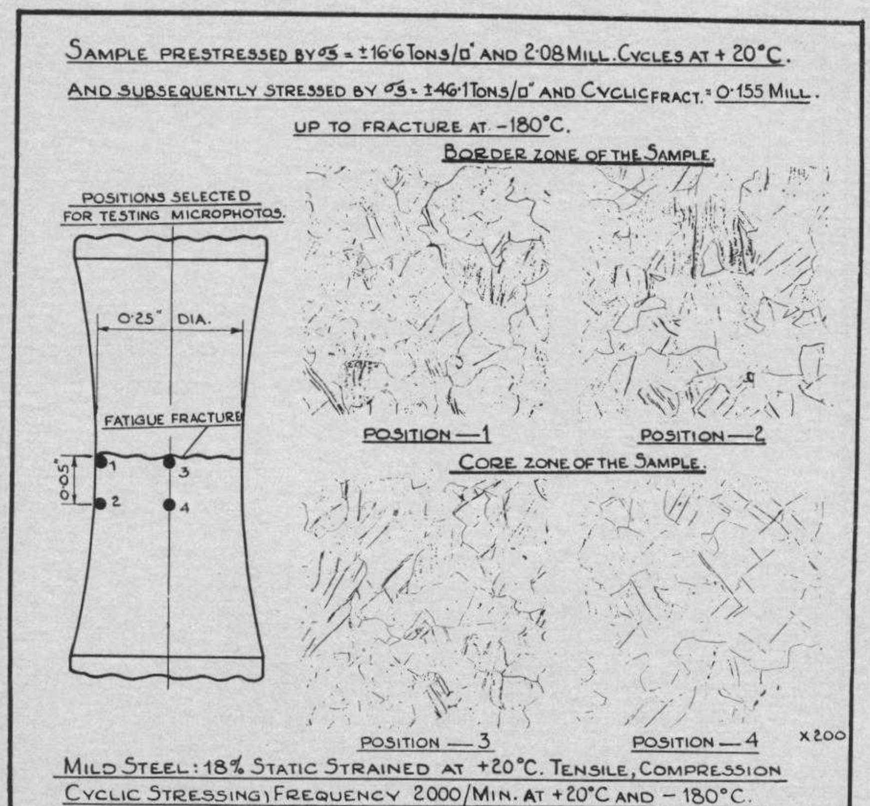
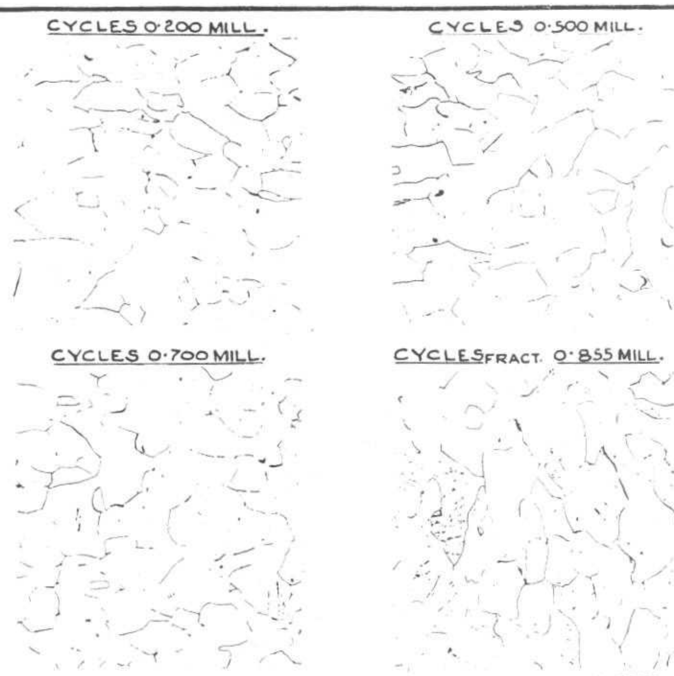


FIG. 10 - APPEARANCE OF PRECIPITATIONS AND TWIN FORMATION IN THE MICROSTRUCTURE OF COLD REDUCED MILD STEEL SAMPLES WHICH HAVE BEEN CYCLIC STRESSED AT +20°C AT FIRST AND SUBSEQUENTLY AT - 180°C.



MILD STEEL: 18% STATIC STRAINED, TENSILE. COMPRESSION
CYCLIC STRESSING $\sigma S = \pm 16{\cdot}6$ TONS/□" FREQUENCY 2000/MIN.,
OIL COOLED.

FIG. 11 - INFLUENCE OF PERIOD OF CYCLIC STRESSING ON THE MICROSTRUCTURE CHANGES OF COLD REDUCED AND CYCLIC SAMPLES MADE FROM M.S.

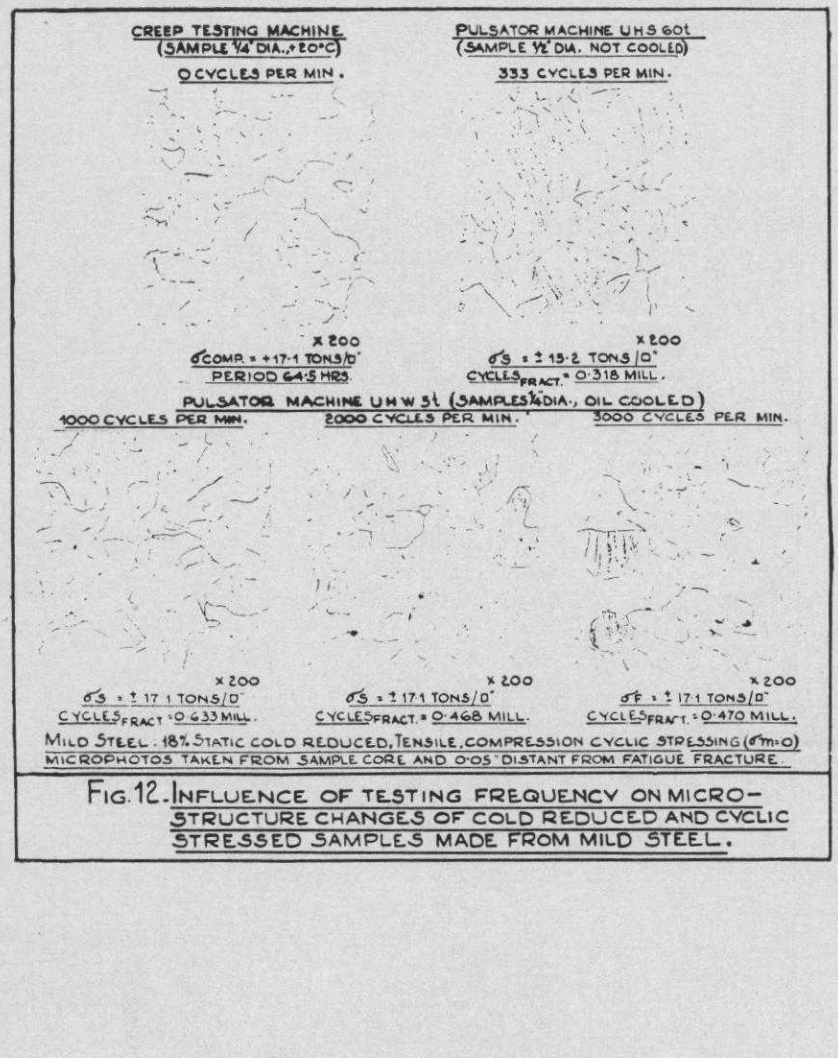


FIG. 12. INFLUENCE OF TESTING FREQUENCY ON MICRO-STRUCTURE CHANGES OF COLD REDUCED AND CYCLIC STRESSED SAMPLES MADE FROM MILD STEEL.

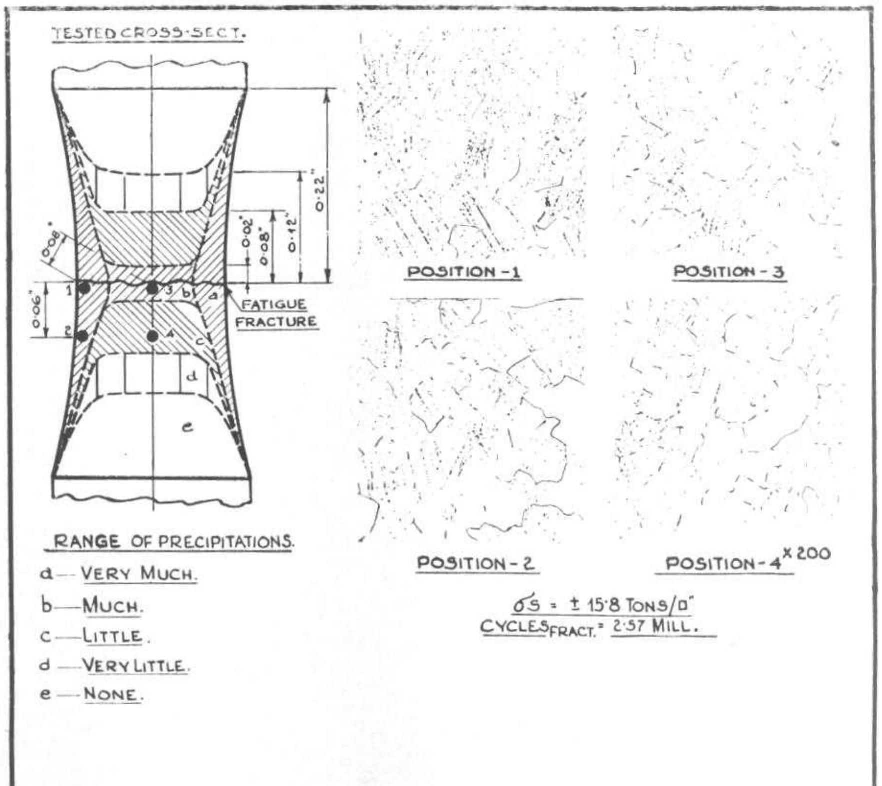


FIG. 13 - DISTRIBUTION OF PRECIPITATIONS ON THE CROSS-SECTION OF COLD REDUCED (6% DYNAMIC STRAINED) AND CYCLIC STRESSED SAMPLES MADE FROM MILD STEEL.

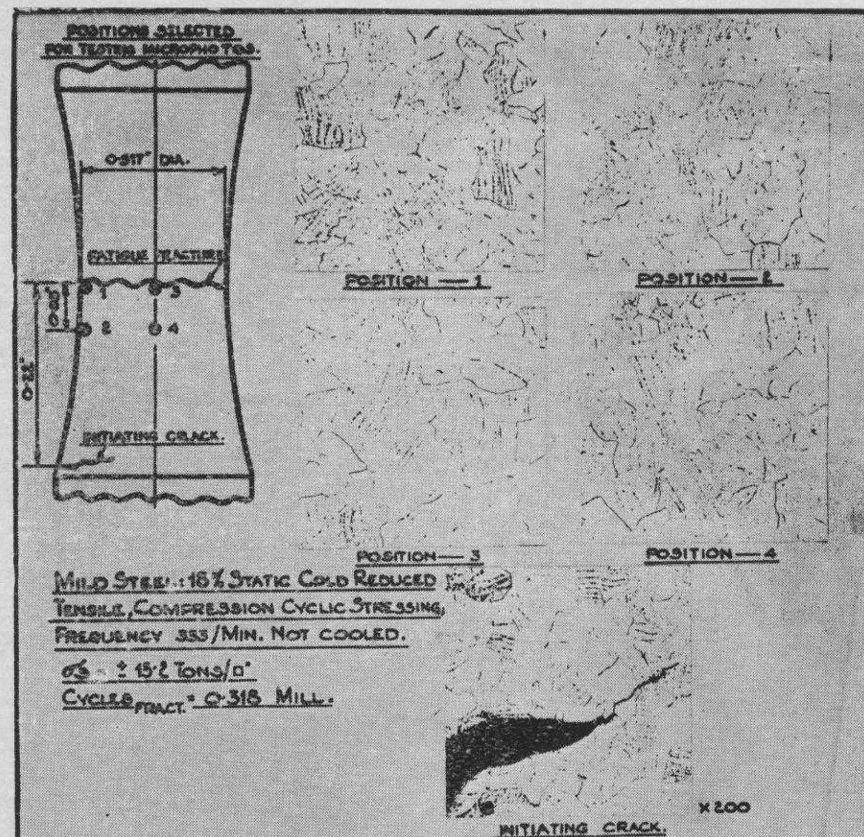


FIG. 14 – PRECIPITATIONS NEAR THE FATIGUE FRACTURE AND AN INITIATING CRACK.

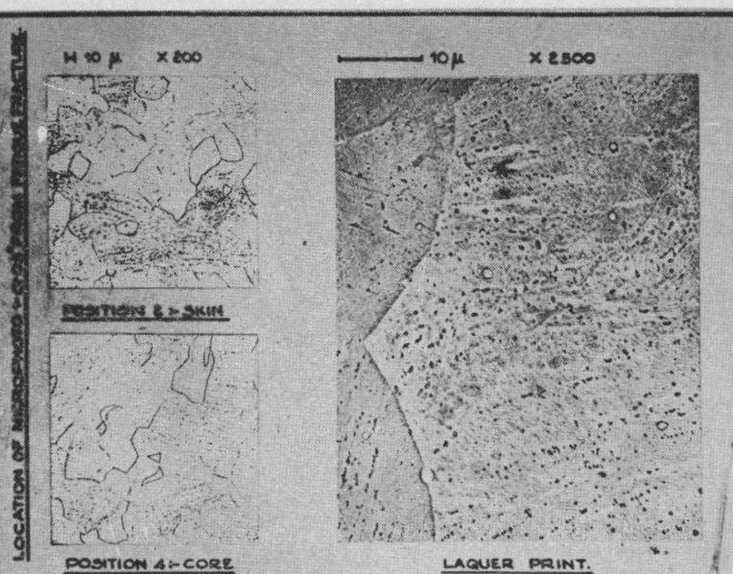
alpha iron. An increase of this effect is to be expected, when the fatigue tests are carried out at elevated temperatures (for instance 200 to 400 deg. C.) The results of these experiments which are still under way, cannot be reported yet. Fig. 15 at left, however, shows, that precipitations occur at elevated temperatures throughout all the crystals. For this test a sample of 1/2" diameter was prestrained under a static load by 18% and subsequently cyclic stressed at a frequency of 1000 per minute. By a little eccentrically stressing, the sample cycled under compression tensile was additionally stressed by bending. Hereby fracture occurred after about 2 hours of stressing (n-0.125 million cycles) outside the test length and the test length was heated up during the last period of the experiment (about 1/2 hour) to about 230 deg. C. In this sample the attempt, to examine the precipitates by means of lacquer print, viewed under the electron microscope succeeded for the first time (vide Fig.15 at right). In this microphoto the boundaries of the crystal grains and the single precipitates in a mostly globular form and arranged along the slip lines are well recognisable. The precipitates have a diameter of less than 1 micron.

VII. SUMMARY

An attempt has been made to explain briefly, the manner in which metallographic methods and X-ray analysis may be employed for investigating into the behviour of cyclic stressed materials apart from mechanical testing methods and what results have been obtained during such examination uptil now. The metallographic observations on cold strained and cyclic stressed specimen have been discussed in detail, which enable us to recognise, that during cyclic stressing changes in microstructure occur, which consist of precipitations and twin formation.

The attempt to determine the heat developed under cyclic stressing and the influence of the testing temperature on the changes observed in microstructure are particularly indicative that local yielding procedures take place together with irreversible place change of atoms at favourable spots. These may be considered to occur as a conditioning stage in the loss of material cohesion and crack formation.

The progress of such initial cracks is mainly an exter procedure and based on stress concentrations caused by notch effects at the crack edges and on the continuously progressing reduction of the actual cross section or the continuously progressing increase in the specific load for the residual cross section respectively.



MILD STEEL: 18% STATIC COLD REDUCED. TENSILE, COMPRESSION, CYCLIC STRESSING. TEST PIECE 1/2" DIA. WITHOUT COOLING, FREQUENCY = 1000/MIN. FRACTURED WITH $\sigma a = \pm 15.2$ TONS/SQ.IN. AFTER 0.125 MILL. CYCLES (2 HRS.) OUT SIDE TEST LENGTH. DURING FATIGUE TEST LENGTH WARMED TO ABOUT 230°C FOR 1/2 HR.

FIG. 15 MICROSTRUCTURE CHANGES IN A COLD REDUCED AND CYCLIC STRESSED TEST SPECIMEN OBSERVED UNDER REFLECTING AND ELECTRON MICROSCOPES.