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Direct Observation for High-Temperature Fatigue in Pure Metals by Means of Microscopic Cine-Camera

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Abstract

To study the mechanism of high-temperature fatigue in pure metals, an apparatus including a microscopic cine-camera combined with the fatigue machine was devised for continuous and direct observations of the specimen surface during the fatigue in vacuum at elevated temperatures. The results obtained in the specimens of poly and single crystals of 99.99% Al and Pb under reversed bending and torsional stress over the temperature range from 0.5 to 0.85 Tm°K are as follows: (1) The grain boundaries move in a way that they are parallel to the directions of the maximum shear stress of the specimen axis. (2) Subgrains generate in single crystals or in coarsed grains under reversed stress and their boundary faces are aligned to be orthogonal as in the above case (1). (3) The surface markings consisting of a series of sharp valleys and peaks due to the polygonized deformation band are found remarkably for the specimen under reversed bending at the testing temperature of about 0.5 Tm°K. The reasons for the characteristics of grain boundary migrations were discussed in connection with the release of the stored energy resulting from the boundary sliding in repetition. And the relationship between the mechanisms of the fatigue failure at low temperature and at high temperature was discussed from a standpoint on the roles of substructure formed during the fatigue.

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I. Introduction

In order to study the mechanism of fatigue in pure metals, this report is intended to investigate dynamically the process of fatigue failure at elevated temperatures higher than their recrystallization temperatures by means of a devised microscopic cine-camera.

Generally, there are diverging views and theories on the mechanism of fatigue in metals. This problem, however, has been considered to depend on when and where the initiation and the propagation of fatigue cracks occur, and how the final fatigue failure comes into existence crystallographically or plastically in the specimens during the fatigue. Notwithstanding the simple appearance, the process of fatigue has not been thoroughly elucidated quantitatively, not to speak of its qualitative aspects. The difficulty in studying the fatigue mechanism may be attributed partly to the fact that the initiation and the propagation of fatigue cracks are controlled delicately by the local stress concentration around various minute defects or the inclusions in the specimen: The effects of such accidental factors make it difficult to draw a definite experimental conclusion in the fatigue process of metals.

But, when the fatigue experiment is carried out at elevated temperatures above the recrystallization temperature, the process of fatigue failure which depends on the type of testing stress or the testing temperature can be made clear more easily, because the local stress concentration due to the piled-up dislocations around various minute defects is gradually decreased by the rearrangement of piled-up dislocations, the so-called "climbing motion".

From the above point of view, the process of fatigue in pure metals with a low melting point such as lead or aluminium were observed microscopically over the testing temperatures from 0.5 to 0.85 Tm°K in this experiments, when Tm is melting point. Consequently, it has been found that the mechanism of fatigue at elevated temperatures is not simple one; firstly, the grain boundary moves in parallel with the maximum shear stress direction of the specimen(1), following which there occur high temperature fatigue cracks due to a repetition of viscous sliding along the original grain boundaries(2) and the subgrain boundaries formed during the fatigue(3), and also due to the formation of deformation bands(4). It has become known that the above fatigue processes take place almost independently or in a combined form depending on their experimental conditions such as the testing temperature, stress amplitide, polycrystal or single crystal structures of the specimens(1)-(4).

However, in a more careful analysis of the structural change under reversed stress at elevated temperatures, it is most desirable to observe the fatiguing specimen surface directly and continuously at each testing temperature for the following reasons. The high-temperature fatigue process may not be essentially observed at room temperature because of the possible occurrence of the structural change due to the annealing effect during the cooling process, e.g., the rearrangement of dislocations. Moreover, when the fatigue process is observed microscopically at room temperature, the

specimen must be removed from the fatigue machine to repeat heating and quenching. The thermal cycling effect should occur in a large or small measure in most metals, not to speak of zinc and uranium, and therefore the continuity of the observed results is questionable. Furthermore, the characteristics of fatigue failure arise another problem as to when, where and how the fatigue cracks initiate and propagate dynamically in the specimen.

For the above reasons, the direct and continuous observations of the high temperature fatigue process by means of the microscopic cine-camera may be regarded as the best experimental technique. This paper describes the characteristics of the devised microscopic cine-camera apparatus and the high temperature fatigue machine containing the vacuum system, in comparison with those obtained by the conventional technique previously reported(1)-(4).

II. Experimental Procedure

1. Devised microscopic cine-camera apparatus for the fatigue test

To observe the specimen surface directly under reversed deformation at a high speed, the following microscopic cine-camera apparatus has been devised(5).

(a) The characteristics of the shutter system in the devised apparatus are shown schematically in Fig. 1(a)(b). A Xenon flash tube is used for illuminating the fatigued specimen surface, and it is triggered synchronizingly at the same phase of reversed fatigue deformation. When the Xe flash tube does not synchronize exactly at the same position of cyclic deformation, it is impossible to observe microscopically the structural change in the fatigued specimen because of the blurring and gradual deviations of focussing as shown by a dotted line in Fig. 1(a). It is evident that the focussing difficulty becomes more pronounced as the magnification of photographing increases. Therefore, a 20 cm disk with a slit of 0.1mm (a) in width is mounted on the shaft of the motor (C) in the site corresponding to the specified observing position of the reversed deformation, e.g., the point O shown in Fig. 1(a). Another disk with the slit (B) is rotated slowly through the reduction gear (D) at the interval of 2 cycles up to the 64 cycles. As shown in Fig. 1(b), a Xenon flash tube is triggered when the photo tube (F) is excited through the coincided slits (A) and (B) by the lamp (E). In this manner, it is triggered synchronizingly at the same position of reversed deformation at the interval of 2, 4, 8, 16, 32, and 64 cycles for a recording of the fatigue process for a long time. Each cut of the film in the cine-camera is wound up very slowly at every flashing.

When the position of the slit (A) in Fig. 1(b) is rotated at the angle of 90 to observe the fatigued structure at the peak stress of tension or compression as shown in Fig. 1(a), it will become possible to record continuously and directly the most important changes in the initiation and propagation of the fatigue cracks. Therefore, this time-lapse technique is considered very effective in quantitatively analyzing dynamic aspects of the fatigue mechanism, especially the role of the positive or negative maximum stress in the propagation mechanism at each cycle.

(b) Other advantages of the device are that the number of cycles and the time lapse are recorded simultaneously on both edges of the same cut of the fatigue process. Accordingly, it is possible to realize the fatigue process microscopically and quantitatively, corresponding to the endurance life or the S-N curve. The testing speed for each cut can be read simultaneously by the timer.

(c) As the fatigued specimen fixed tightly on the both grips of the machine cannot be observed wholly, the apparatus was devised to be able to move in all directions fractionally. A sharp notched specimen is in wider use to observe the structural change, but this technique is no more than a means for convenience and is not recommendable in view of complexity of the stress distribution at the bottom of the sharp notch. Therefore, in the present study, a double transfer system with low magnifications of x1, x2, x4, x8 and high magnifications of x10, x20, x40 and x80 has been employed to observe the over-all behaviors of specimens, with greater emphasis on the macroscopic observations.

2. Characteristics of the devised vacuum and high temperature fatigue machine

It was unexpectedly difficult to devise a fatigue machine which is capable of carrying out the fatigue test in vacuum at elevated temperatures and of photographing microscopically through a silica glass eyehole. In such a case, consideration should be given not only to improve the convenience for the continued observation but also to maintain the dynamic capacity and endurability, especially in vacuum, as required for a fatigue machine(5). Particular attention was paid to the following points:

(a) For the purpose of damping the vibration in the machine for the microscopic observation, the machine was constructed with a special angle material of a honeycombed structure to improve the rigidity, and hardened rubber was used for a structural material. As a result, the vibration was diminished to a negligible extent. (b) The cloudiness of the silica glass eyehole due to sputtering was prevented by means of a shutter which is driven electromagnetically and synchronizingly with the triggered circuit just before photographing. (c) The problem in adiathermancy between the heated specimen and the main movable part was solved by water cooling through a hollow of the main shaft and by using the strengthened brick ("Micalex") as a structural material. (d) To remove the effect of thermal stress on the specimen due to heating before testing, it was devised to be able to tighten the free end of the specimen with the Wilson shield when heated up to a specified temperature. (e) Besides, the form of stress wave, endurance and reproducibility as a fatigue machine were carefully considered. However, the life of bellows for air tightening with the main driving shaft became a problem. (f) It can be expected that the testing atmosphere has an effect on the fatigue endurance or its mechanism, especially on the propagation speed of fatigue cracks. In a considerable number of research on it(6)-(9), there is a report that the fatigue endurance of copper and some other metals is prolonged lineally with the increasing degree of vacuum(7). Moreover, the continuous observation for the high-temperature fatigue process in the present experiment will become impossible when the specimen surface is oxidized in air atmosphere. Therefore, the fatigue test was programmed in high vacuum by attaching the

10 ℓ/sec ion getter pump, and the change in the vacuum degree during the fatigue test was checked by means of the electronic type vacuum recorder. (g) When the dimensions of the specimen are changed for different experimental purposes, the principal part of the machine including the specimen axis is devised in a way that it can ascend or descend to set the specimen surface within the focus of the objective lense by inserting the liner of varied thickness.

The other functional capacity of the machine may be summarized as follows: (a) The mechanism of the fatigue machine is similar to the Schenck type reversed bending and torsional machine, that is, the reversing motion is mechanically driven by rotating the eccentric crank. Hence, this devised fatigue machine is of a so-called constant deflection type. (b) The capacity of the machine is variable in three stages of $\pm$ 1 Kg-m, $\pm$ 0.5 Kg-m and $\pm$ 0.2 Kg-m. For measurements of the reversed stress, the cross type wire strain gauge attached to the torque bar is connected with the pen-writing oscillograph. (c) The testing speed of the machine is variable in the range from 30 cpm to 1500 cpm by the 1 HP D. C. motor. (d) The maximum amplitude at the driven grip is $\pm$ 8m/m for bending, and the maximum twisting angle is $\pm$ 12° for torsion. Further details of the devised machine will be omitted here. The outlook of the devised apparatus is shown in Photo. 1.

The testing temperatures ranged from 0.5 to 0.85 Tm°K: The maximum testing temperature was 500°C for 99.99% aluminium specimen and 250°C for 99.99% lead specimen. For selection of the testing temperatures, the high-temperature fatigue phenomenon was analyzed by using the homologous temperatures θ ($\theta = T/T_m$°K) as a measure of testing temperature, irrespective of the metals used. It can be expected that the fatigue phenomenon of lead observed at room temperature ($\theta = 0.48$) corresponds to those at 200°C for aluminium and at 650°C iron.

For estimation of the testing stress, the maximum nominal stress was used from the conventional elastic equation based on the normal S-N curve. The surface stress estimated would give its relative value.

III. Results of the Direct Observation

1. Characteristics of grain boundary migration and subgrain growth under the fatigue

Photos. 2(s)-(c) show the coarse grained lead specimen which was annealed for 2hr at 300°C and then fatigued at 250°C at 100 cpm under the reversed torsional stress of $\pm$ 0.05 Kg/mm^2 in the partial vacuum of 1mmHg to promote the occurrence of fatigue cracks. The two square traces on the left half side in these photograph are 100 gr micro-Vickers' markings independent of the fatigued structures. The photograph (a) shows the structural change after fatigued only by 2 cycles, in which the grain boundary migration begin to occur locally in parallel with the maximum shear stress direction as shown by the two arrows A and B. The photograph (b) shows the right triangle traces exactly in parallel with the maximum shear stress direction due to the grain boundary migration after fatigued by about 100 cycles as shown by B-B' and A-A'. It is found clearly from the photograph (b) that the direction of the grain boundary migration is exactly in parallel with the maximum shear stress direction(1).

Furthermore, the photograph (c) shows the fatigued surface structure by 1900 cycles, with the occurrence of the slip lines and the growth of subgrains during the fatigue. Especially, it is ascertained that the subgrain boundaries (c), (d) formed during the high temperature fatigue are also aligned in parallel with the maximum shear stress directions(3).

The results observed on the characteristics of grain boundary migration are summarized as follows(1): (a) The shape of grain boundaries becomes from curvilinear to linear, and the migration direction corresponds exactly with the maximum shear stress direction, i.e., at the angle of 0° and 90° for torsion and at the angles of $\pm 45^\circ$ for bending. As a result, the polycrystal grain boundaries which were in irregular arrangement before the experiment are aligned orthogonally. The above characteristics are the phenomena peculiar not only to the metal surface but also to its interior. (b) The dark striations regarded as traces of the grain boundary migration is chiefly caused by the uneveness of the migrated site due to an alternate repetition of the boundary migration and slidings.

And the results obtained on the fatigue cracks of pure metals due to slidings along the subgrain boundaries at elevated temperatures are summarized as follows (2)(3): (a) When a single crystal of pure lead or aluminium was under the repeated stress at elevated temperatures, the initiation and growth of subgrains took place, accompanied by a migration of the subgrain boundaries in the direction of the maximum shear stress of the specimen axis. Their grain boundaries were aligned nearly orthogonally in argon atomosphere or vacuum, and along the boundaries slidings of the subgrains occurred with one another and formed cracks. In air atomosphere the alignment of the boundary in the direction of the maximum shear stress was not complete, resulting in a poor alignment of cracks. (b) In the case of polycrystals, it was observed that coarse grained specimens showed the same behavior as in the single crystal in the case of a large amplitude of the reversed stress, but under a lower stress the migration and alignment of the original grain boundary in the directions of the maximum shear stress played an important role in the crack formation. (c) The size of subgrains formed in the fatigue-failured single crystal specimen depended appreciably on the testing temperature. Generally, the size became smaller with the decrease of temperature and the prolongation of endurance life. (d) It was found that the main mechanism of the high-temperature fatigue cracks resulted from the slidings along the subgrain boundaries formed during the fatigue.

The above observation placed its emphasis on the high temperature fatigue process of the single crystal having no grain boundary. However, such a basic, preliminary experiment has not been made heretofore(10). The relationship between the crystal orientation and subgrain boundary fatigue cracks is yet to be studied, but it appears from the above discussion that the crystal orientation would not exercise a considerable effect on the authors' conclusion in the present study.

2. Abnormal growth of the deformation band

The single crystal lead specimen was fatigued by 10^5 cycles of the reversed bending stress of ± 0.8 Kg/mm^2 in air at room temperature and chemically polished to remove the surface relief. Then, Photos. 3(a)-(c) show structural changes of the specimen when the stress amplitude is raised up to ± 1.2 Kg/mm^2. The photograph (a) shows the specimen surface after further fatigued by 30×10^2 cycles, in which the surface markings indicated by the arrow begin to grow in the direction at the angle of $\pm 45^\circ$ against the specimen axis. The photograph (b) exhibits a more remarkable occurrence of the deformation bands fatigued by 60×10^2 cycles, in which they begin to grow up in the direction at the angle of $\pm 45^\circ$ against the specimen axis. Furthermore, the photograph (c) shows the abnormally grown deformation bands consisting of sharp valleys and hills after fatigued by 477×10^2 cycles. The fatigue cracks occur frequently along the bottom of the above-mentioned sharp valleys due to the macroscopic stress concentration(4). It is noticeable that the structural change is clearly photographed even when the testing speed is as fast as 1150 cpm. The continuous observation in the paragraph (2) shows general characteristics of the high temperature fatigue process just above the recrystallization temperature, because the homologous temperature θ (θ = T/Tm°K) of lead is about 0.5 at room temperature.

The results observed on the fatigue cracks of pure metals due to the deformation band at elevated temperatures are summarized as follows(4): (b) The surface makings consisting of a series of sharp valleys and peaks were observed under the reversed bending stress in the temperature range of about 0.5 Tm°K. The shape of the valleyes and hills varied with the testing temperature. The most sharp markings were found in the vicinity of 0.5 Tm°K, and these markings became indistinct at temperatures lower and higher than 0.5 Tm°K, where Tm is a melting point. (b) At the critical temperature of 0.5 Tm°K, it was found that the fatigue cracks of the tensile type due to the stress concentration were initiated at the bottom of sharp valleys, and also that the cracks of the shear type due to the sliding of subgrain as described in section III-(1) occurred along the boundaries between the markings and the matrices. (c) It was ascertained that these markings were consisted of unique deformation bands which were developed remarkably by the climbing and alignment of dislocations during repetition of the reversed deformation.

However, in the above experimental results the effect of the crystal orientation on the formation of deformation bands was not analyzed. It is well known in the creep process that the banding behavior or the cell formation depends on the crystal orientation as the function of experimental temperature, and that the banding behavior becomes remarkable especially in specimens of the single slip orientation in the vicinity of <110>. However, no definite elucidation on the banding behavior made in relation to the crystal orientation, experimental temperature and atmosphere, and the magnitude of stress amplitude during the high-temperature fatigue. Therefore, the authors intend to carry out a more systematic experiment on the basis of the present preliminary observation.

IV. Discussion of Experimental Results

As clearly shown in Photos 2 and 3, it is most characteristic that the grain boundaries move in parallel with the maximum shear stress direction of the specimen axis(1). Secondly, it is found that the abnormal deformation bands consisting of sharp valleys and hills are formed and connected directly with the fatigue cracks which occur at a high temperatures in the vicinity of about 0.5Tm°K(4). The growth process of the abnormal deformation band peculiar to the fatigue is shown in Photo. 3 distinctly and continously. Thirdly, it is confirmed from Photos. 2(b), (c) that the sub-grains formed in the single crystal or polycrystal of aluminium and lead during the fatigue are aligned in parallel with the maximum shear stress direction as in the case of polycrystal metals and the subgrain boundaries contribute to the formation of fatigue cracks(3).

From the above findings it may be said safely that the results and discussion on the high temperature fatigue mechanism in the author's previous reports (1)-(4) are warrantable. Accordingly, this indicates that the aim of the device in the fatigue machine is almost attained and its capacity is in a satisfactory condition.

1. On the characteristics of grain boundary migration

It was made clear from the Photos. 2 (a)-(c) that the grain boundary becomes lineal and its moving direction coincides exactly with the maximum shear stress directions at the early stage of the fatigue process at elevated temperatures. Such characteristics of the boundary migration were not confirmed experimentally by the process of normal recrystallization or under the unidirectional deformation such as a creep (11)(12). Therefore, the experimental results will be discussed from the viewpoint of the dominant factors for the grain boundary migration and the characteristics of fatigue stress.

Generally, the causes of the grain boundary migration have been considered on the basis of several mechanisms (13)(14). For example, (a) The surface tension to move the grain boundary to the center of the curvature; (b) The force to move the grain boundary in a direction where grains of small strain energy are grown up to decrease the stored energy of the total system; and (c) The force to move the grain boundary in the direction to decrease the strain energy, when the stress at the grain boundary due to slidings can be released by the coundary migration. It will be considered from the present experimental conditions that the above characteristics of the grain boundary migration are closely related with the factors (b) and (c), especially (c).

It is known that the mechanism of the grain boundary migration and the grain boundary structure depend largely upon the magnitude of the boundary angle, the symmetry of grain boundary, and the boundary orientation itself. That is, (i) in the case of a small tilt boundary, the boundary moves easily as a simple migration of the dislocation wall in their slip planes as observed previously in zinc at room temperature by Parker and Washburn(15). Whereas, the migration becomes difficult with an increase of the tilt angle.

(ii) In the case of the non-symmetrical boundary (13)(14)(16), the dislocation should move in parallel with their slip planes, with the vertical climbing motion. The climbing motion of the dislocations will not occur at low temperatures becasue of the difficulty in the diffusion of atoms. However, the grain boundary can move in accordance with the diffusion velocity at high temperatures above 0.5 Tm°K. (iii) A large angle boundary with amorphous structure consisting of many vacancies can move freely from one crystal lattice to another (13)(14). Accordingly, it is assumed that most of the grain boundaries can move, though there is some difference in the moving mechanism and mobility. It can be also predicted that the driving force of the boundary migration is produced from the strain energy stored by each cycle of deformation.

To discuss the characteristics of the grain boundary migration mentioned in Chapter III, the effects of the slips in the grain matrix on the grain boundary migration should be first taken into consideration. It is obvious that the main mechanism of deformation is the slip mechanism due to the motion of dislocations, even if the deformation occurs at elevated temperatures. Accordingly, the strain energy along the boundary faces should be increased by piled-up dislocations during the slip process. Therefore, the boundaries are considered to move in a direction to decrease the strain energy as described in the mechanism (b). Besides, there are four sorts of the slip planes as $\{111\}$ and twelve sorts of the slip directions in the face centered cubic crystals such as lead and aluminium experimented in this report. In addition, as non-octahedral slips(17) such as $\{100\}$ would occur with a further increase of temperature, a more isotropic deformation can be expected in the f.c.c. metals. Hence, the slip occurs frequently in or near the maximum shear stress direction, and therefore the dislocations are piled up around the grain boundary in the maximum shear stress direction. This results in an uneven distribution of the strain along the grain boundary.

Therefore, it may be realized that the grain boundary can move in the maximum shear stress direction, in order to reduce the strain energy. However, the migration of one of the two neighbouring grains depends on the number and Burger's vector of the dislocations piled up around each grain boundary. Consequently, the grain boundary can not move reversely but in the unidirection in spite of the reversed deformation, except for the optimum experimental condition as carried out by Parker (15). From the above consideration, it is expected that the grain boundaries move frequently in the maximum shear stress direction. However, when the driving force of the boundary migration depends on the strain energy due to the slip process, the direction of a boundary migration does not coincide exactly with the maximum shear stress direction becasue of its dependance upon their crystal orientations. Therefore, it is difficult to explain the reason why the grain boundary migration coincides exactly with the maximum shear direction as shown in the photos. 2, (a)-(c).

There is a deformation mechanism other than the slip mechanism at elevated temperatures: It is a grain boundary sliding mechanism and is predominant over the slip mechanism when the total strain decreases and the testing temperature increases (11)(18). Generally, the sliding of grain boundaries becomes difficult with increase of the stored strain, but it is promoted again when the stored strain is released by the boundary migration. As already mentioned in a previous report (1), it has been ascertained that the dark striations due to the grain boundary migration do not result from a thermal etching but mainly from a surface roughness due to the alternate occurrence of the migrations and slidings. This shows that the boundary sliding contributes greatly to the driving force of the grain boundary migration.

Furthermore, to consider the mechanism of the grain boundary migration due to the boundary sliding, a schematic model is proposed as shown in Fig. 2. When the two arrows in this figure show the direction of the maximum shear stress, it is found easily that the grain boundary sliding occurs mostly in the vicinity of the positions A and B as shown in Fig. 2. On the other hand, in the vicinity of the position C, the normal stress such as tension and compression is dominant and the shear component is almost negligible, as shown in Fig. 2. Accordingly, the strain due to the boundary sliding along the positions A and B in Fig. 2 is mostly piled up near the position C, and the boundary may move as indicated by C_1 or C_1'. When the original boundary ACB moves in the maximum shear direction such as AC_1B or $AC_1'B$, it is considered that the piled-up strain energy due to the boundary sliding decreases in proportion to the amount of the migration and attains a more stable state.

It may be said that Photos. 2 (a)-(c) represent the results of the boundary sliding process mentioned above. Generally, if the amount and the direction of boundary slidings should be equivocal and reversible ideally in the positive and negative cycles, the strain along the position C in Fig. 2 would be released by each cyclic deformation, and consequently, the grain boundary migration and the fatigue failure would never take place. However, in practice, the positive and negative boundary slidings are irreversible, and the integral of the differential strain at each cycle is accumulated gradually during the irreversible fatigue deformation. And, when the total strain energy overcomes the surface tension along the boundary faces, the boundary may move gradually in the maximum shear stress direction.

It is supposed that the same phenomena as shown in Fig. 2 occurs under a unidirectional deformation such as a creep. But, even if the strain are piled up along the position C in Fig. 2 the strain will be released due to the unidirectional vacancy flow in the case of creep (11)(12). On the other hand, the vacancies would flow inversely under tension or compression during the fatigue. Therefore, it is expected that the unidirectional vacancy flow of the creep is by far greater than that of the fatigue, regardless of the fatigue condition such as the testing speed or temperature. Accordingly, in the fatigue process, the stored strain energy along the position C in Fig. 2 can hardly be released due to the vacancy flow, and the grain boundary seems to move exactly in the maximum shear stress direction.

2. Relationship between the low and high-temperature fatigue mechanisms

Since about ten years ago, much has been studied about the fatigue

mechanism of pure metals by microscopic observation and direct transmission-electron-microscopy using thin film specimens. Let us discuss the relationship between the tendency of recent researches and the high-temperature fatigue mechanism obtained by the present authors.

It has been reported that the fine crystallites are localized in the tip of fatigue cracks or in its neighbourhood, especially when fatigued under a high amplitude of stress. In an early work, Gough(19) reported that the fragmentation of fatigue failured crystals about 10^{-4}cm in size occurred on the fractured surface by a X-ray technique. These findings have recently been confirmed by several workers (20)-(22); even at such a fairly low temperature, as -186°C, the fragmentation of copper or iron never fails to occur in the neighbourhood of a fatigue-failured region due to an intense cold work enough to cause the final fracture. However, unlike the present authors' experiment, the viscous sliding along the fine sub-boundaries should not occur in their experiments which were carried out at a low temperature.

V. Summary

In order to experimentally investigate the high-temperature fatigue mechanism, the authors devised a vacuum and high-temperature fatigue machine containing a specially mounted 16m/m microscopic cine-camera which can photograph synchronizingly with the deformation phase, and succeeded in recording the fatigue process at elevated temperatures dynamically and directly.

The results obtained in the authors' previous works have been confirmed directly and dynamically by the present device: (a) The grain boundary migrates exactly in the maximum shear stress direction of the specimen axis during the high-temperature fatigue(1). (b) In like manner the subgrains having occurred during the fatigue developed in the maximum shear stress direction, and then the fine subdivision of the crystals which led directly to fatigue cracks comes into existence(3). (c) The deformation bands show an abnormal formation and growth in the vicinity of 0.5Tm°K, followed by the formation of sharp macroscopic uneveness peculiar to the fatigue(4).

The fact that the grain boundary migration proceeds exactly in the maximum shear stress direction can be attributed largely to the release of the strain energy stored by the repetition of boundary slidings. In addition, the release of the strain energy due to the occurrence of slips in the matrix almost parallel to the maximum shear stress direction would promote the above tendency. In view of the fact that under repeated stresses the amount of the unidirectional vacancy flow is small as compared with that of creep, the above-mentioned characteristic grain boundary migration would not occur in the case of creep and can be regarded as a phenomenon peculiar to the fatigue. And, the relationship between the mechanisms of the fatigue failure at a low temperature and at a high temperature was discussed from the viewpoint of the role of the substructure formed during the fatigue.

Acknowledgements

The present research was financed by the First Grant-in-Aid for Scientific Researches of the Tōyō Rayōn Foundation. The authors wish to express their appreciation to Prof. Hidezi Suzuki, the Department of Science, the University of Tokyo, for his helpful discussion on the mechanism of grain boundary migration, and also to Mr. Takao Matsui, President of the Miki Industrial Co., Ltd. for the cooperation in manufacturing the microscopic cine-camera device.

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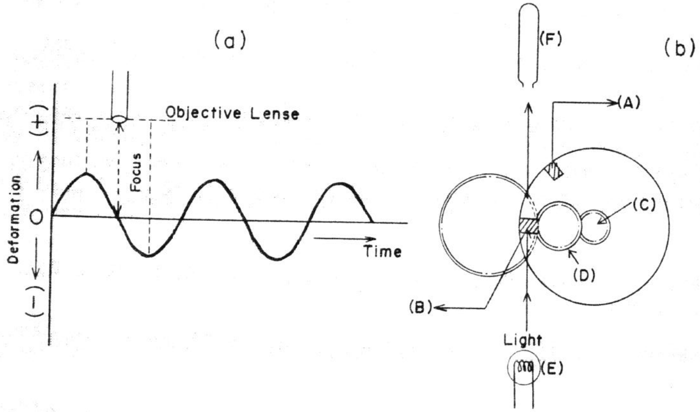

Fig. 1. Shutter system in cine-camera apparatus for synchronizing with deformation of specimen;
(a) observing positions in cyclic deformation.
(b) shutter system. (A) and (B): slits, (C): shaft of motor. (D): reduction gear, (E): exciter lump, (F): photo tube.

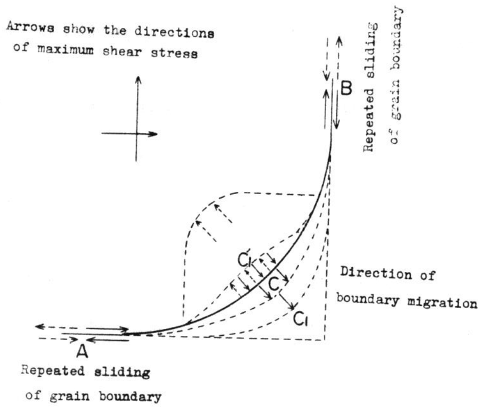

Fig. 2. Schematic representation of grain boundary migration under reversed stress.

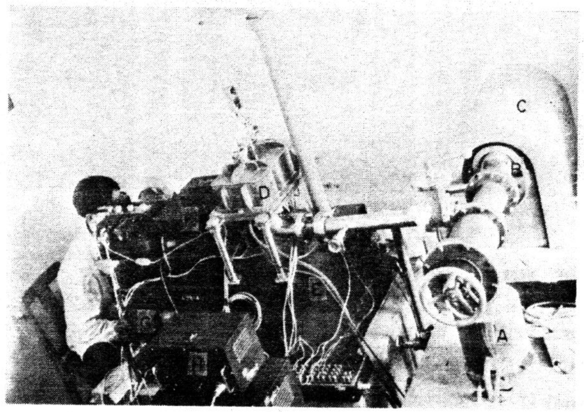

Photo. 1. General view of apparatus including microscopic cine-camera, fatigue machine and vacuum system.
(A) Oil diffusion pump, (B) Ion getter pump,
(C) Baking furnace for (B), (D) Vacuum chamber fatigue machine,
(E) Frame of machine, (F) Microscopic 16m/m Cine-Camera,
(G) Synchronizing shutter, (H) Amplifier for Xe flash tube.

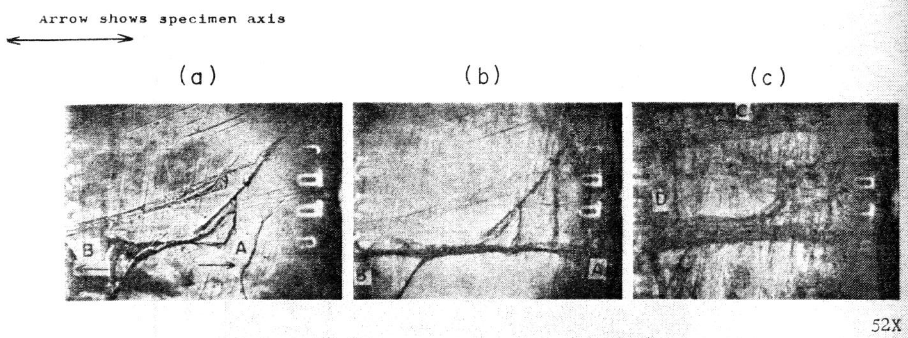

Photo. 2. Microphotograph of grain boundary migration and subgrain in coarse grained Pb specimen under reversed torsional stress, $\pm$ 0.05 Kg/mm^2 in partial vacuum of 1mmHg at 250°C.
(testing speed : 100 cpm)
(a) after 2 cycles (b) after 116 cycles
(c) after 19 x 10^2 cycles.

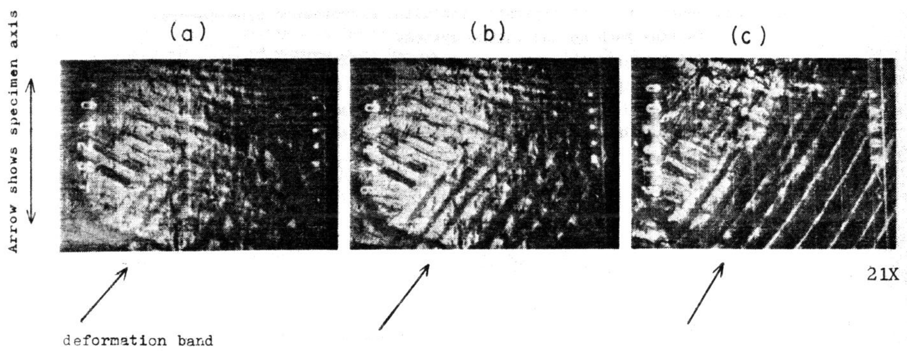

Photo. 3. Microphotograph of occurrence of deformation band in Pb single crystal specimen under reversed bending stress, $\pm$ 1.2 Kg/mm^2 in air at room temperature.
(testing speed : 1150 cpm)
(a) after 30 x 10^2 cycles, (b) after 60 x 10^2 cycles,
(c) after 477 x 10^2 cycles.