EFFECT OF SUPERIMPOSED SMALL VIBRATIONS ON THE STATIC CREEP BEHAVIOUR OF POLYCRYSTALLINE ZINC*

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Torsional vibrations of increasing amplitudes were superimposed on pure polycrystalline zinc wires of different grain sizes while being crept under relatively high tensile stresses and temperatures. It was found that increasing the alternating shear strain amplitude of the imposed vibrations first decreased the steady creep rate to a minimum value followed by an increase which continued until the wire failed. The observed initial decrease in the creep rate was found to be in some cases as large as a factor of five times at room temperature. The shear strain amplitude at which the minimum in the creep rate was found showed a dependence on temperature, frequency of vibration and the grain size of the test sample. On increasing any of these parameters this minimum occurred at smaller shear strain amplitudes. The initial hardening and subsequent softening of the material as the strain amplitude increased was attributed to a vacancy generation and pinning mechanism followed by vacancy annihilation and dislocation climb.

EFFETS DE PETITES VIBRATIONS FORCEES SUR LE COMPORTEMENT EN FLUAGE STATIQUE DU ZINC POLYCRISTALLIN

On a appliqué des vibrations de torsion d'amplitudes croissantes à des fils polycristallins de zinc pur, de tailles de grain différentes. Pendant ces essais, les fils étaient soumis à un essai de fluage sous des tensions de traction et à des températures relativement élevées.

On a observé qu'un accroissement de l'amplitude alternative de la déformation de cisaillement des vibrations appliquées, la vitesse de fluage statique décroît d'abord jusqu'à une valeur minimum puis s'accroît jusqu'à la rupture du fil.

La vitesse initiale de fluage est dans certain cas diminuée dans un rapport 1/5 à la température ambiante. L'amplitude de la déformation de cisaillement pour laquelle le minimum de la vitesse de fluage est observé, dépend de la température de la fréquence de la vibration et de la taille de grain de l'échantillon. Si on accroît l'un de ces paramètres, le minimum de la vitesse de fluage apparait pour des amplitudes plus petites de la déformation de cisaillement. Le durcissement initial et l'adoucissement subséquent du matériel lorsque l'amplitude de la déformation augmente, sont attribués à la formation de lacunes et à un mécanisme d'ancrage suivi d'une disparition de lacunes et d'une montée de dislocations.

DER EINFLUSS KLEINER ÜBERLAGERTER SCHWINGUNGEN AUF DAS STATISCHE KRIECHVERHALTEN VON POLYKRISTALLINEM ZINK

Torsionsschwingungen mit zunehmender Amplitude wurden reinen polykristallinen Zinkdrähten unterschiedlicher Korngröße während des Kriechens bei relativ hohen Zugspannungen und Temperaturen überlagert. Es wurde gefunden, daß bei einer Erhöhung der Amplitude der Torsionswechseldehnung der angelegten Schwingungen die statische Kriechgeschwindigkeit zuerst bis zu einem Minimum abnahm und dann wieder zunahm bis zum Bruch der Probe. In einigen Fällen nahm die Kriechgeschwindigkeit bei Raumtemperatur am Anfang um bis zu einem Faktor fünf ab. Die Schubspannungsamplitude, bei der das Minimum der Kriechgeschwindigkeit auftrat, zeigte eine Abhängigkeit von der Temperatur, von der Schwingungsfrequenz und von der Korngröße des Untersuchungsmateruals. Bei einer Zunahme eines dieser Parameter erschien das Minimum bei kleineren Amplituden. Die anfängliche Verfestigung und nachfolgende Entfestigung der Proben mit zunehmender Dehnungsamplitude wird zurückgeführt auf einen Mechanismus mit Leerstellenerzeugung und Verankerung, gefolgt von Leerstellen-annihilation und Klettern von Versetzungen.

1. INTRODUCTION

In the course of a previous study by the authors[1] on the anomalous creep of polycrystalline zinc in tension, the internal friction of the samples was measured while undergoing creep. It was noticed that the steady creep rate of the sample showed some sensitivity to the strain amplitude of vibration during the internal friction measurements, particularly when the strain amplitude was increased above the level of 10^{-6} at which the measurement was usually made. This observation together with the technical importance of the effect of superimposed vibrations on the creep properties of loaded materials presented the motive for a thorough study of this effect. Kemsley and Paterson[2] observed that the work hardening of copper crystals in alternating straining was less than in a tensile test. Vreeland,[3] working on zinc bi-crystals, found that modulating the permanent stress by a small alternating component decreased the slipping of dislocations and diminished the plastic flow. Meleka and Evershed[4] reported that the

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superposition of a fatigue stress on a copper specimen under creep conditions caused a sudden increase in the creep rate.

The aim of the present work was to perform a more systematic study at different temperatures of the creep behaviour of zinc polycrystals of different grain sizes under combined stresses of static tension and alternating shear.

2. EXPERIMENTAL DETAILS

The zinc wires used in the present investigation were of spectroscopic purity (supplied by Johnson–Matthey's Co) and of uniform diameter 0.5 mm. Polycrystalline samples were given different amounts of heat pulses under vacuo to provide a series of tests samples with different grain sizes ranging between 0.015 and 0.8 mm. The wire sample was tightly gripped from its two ends in a tensile creep machine the details of which were described elsewhere.[5] The tensile strain was optically measured with a strain sensitivity of 10^{-4}. A light but rigid metallic vane, V, was fixed on the midpoint of the test wire and was made to project partially over a parallel rigid and fixed copper electrode for electrostatic excitation (Fig. 1 in Ref. 5). Forced torsional vibrations were induced into the wire sample by applying a controlled alternating electrostatic torque between the metallic vane, V, and the exciting plate. The fixed lower electrode was also connected to a micro-vibration detector of a type previously described.[6] The capacity changes induced by the torsional vibrations of the test wire were translated through the vibration detector to voltage variations displayed on an oscilloscope. The length of the trace on the oscilloscope screen allowed the determination of the vibration amplitude, A, of the metallic vane, V.

In order to study the dependence of creep rate on the vibrational shear strain amplitude, the specimen was set into vibrations the amplitude of which was then increased in steps through the exciting voltage. The actual amplitude, A, of the vane, V, was measured by a travelling microscope and the corresponding vibrational shear strain amplitude, θ, of the test specimen (Fig. 1) was then calculated using the formula:

$$\theta = rA/hL,$$

r being the radius of the test wire, L half its length, and h half the length of the exciting vane, V. The relation between the shear strain amplitude and the output indication of the oscilloscope was found to be linear. In order to measure large amplitudes for which the length of the trace on the oscilloscope screen exceeded the screen diameter, the amplification of the calibrated amplifier of the cathode-ray oscilloscope was reduced by a known factor. In this way the measurement of strain amplitudes in the range 10^{-7} to 10^{-4} was made possible.

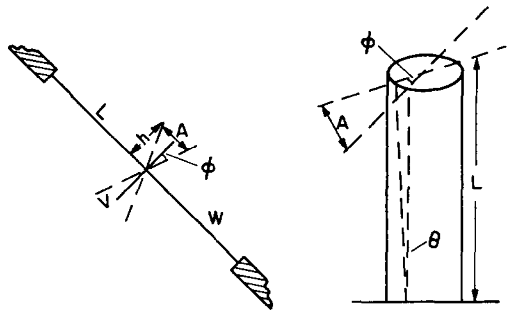

FIG. 1. Calculation of the shear strain amplitude, θ, of the wire sample: r being the radius of the wire, L half its length, h half the length of the vane, and A the actual amplitude of the vane.

The temperature of the sample was changed by thermostatically controlled furnace with maximum temperature fluctuation of about ± 0.5°C at 200°C.

3. EXPERIMENTAL PROCEDURE AND RESULTS

Tensile creep tests under different stresses were made at different temperatures on zinc polycrystals of different grain sizes. After a steady creep rate was attained in each case, superimposed vibrations having a controlled small amplitude were then induced in the specimen and the steady creep was allowed to proceed further for an interval of time. The strain amplitude of the induced vibrations was increased in steps and maintained constant during each step for a certain interval of creeping time, until finally the wire failed. From a plot of the strain–time relation the steady creep rate of the specimen corresponding to each strain amplitude of vibration was determined.

Typical representation of three creep tests at 20, 50 and 75°C for samples having mean grain diameter 0.018 mm is shown in Fig. 2. The steady creep rate, $\dot{e}$, of the test sample showed a decrease after the application of vibrations of small strain amplitude. As the amplitude was increased, a further decrease in $\dot{e}$ was observed until a certain amplitude was reached after which the steady creep rate of the sample began to increase progressively until fracture. The relation between the shear strain amplitude, θ, of the induced vibrations and the corresponding steady creep rate is shown in Fig. 3. A minimum point was found in every ($\dot{e}$–θ) curve. The position of this minimum on the vibration amplitude axis was found to be highly sensitive to temperature. For higher temperatures the minimum became sharper and shifted its position towards smaller strain amplitudes.

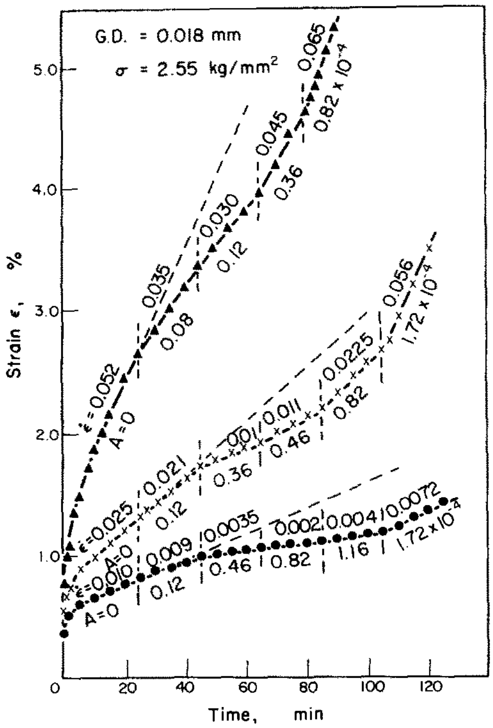

FIG. 2. Creep curves taken at different temperatures for samples having an average grain diameter 0.018 mm. Pulses of vibrations of increasing strain amplitudes were successively superimposed on the sample after the steady state creep had been reached. The strain amplitudes, θ, and the associated steady creep rate, $\dot{\epsilon}$, in $(\min)^{-1}$ are given on the curves.

The grain size dependence was also investigated. The experimental run was repeated on samples having grain diameters 0.05 mm and 0.15 mm at different temperatures. Results are shown in Fig. 4. It could be remarked that for coarse-grained samples the minimum in the ($\dot{\epsilon}$–θ) curves became sharper and occurred at smaller values of strain amplitudes.

When samples, cold-worked by plastic torsion, were tested it was found that the sensitivity of the creep rate to vibrations decreased in magnitude with the increase of cold-work.

It was also thought that the frequency of the imposed vibrations might have some influence on the change in the steady creep rate of the test sample. Experiments were thus carried out on samples vibrated at different frequencies. Fig. 5 shows the results of observations taken on samples having average grain diameter 0.018 mm. It was found that as the frequency of vibration increased, the minimum in the ($\dot{\epsilon}$–θ) curve became sharper and its position shifted towards smaller strain amplitudes.

From the above results it was concluded that the increase in temperature, grain size, and frequency of vibration enhanced the mechanisms responsible for the decrease and subsequent increase in the steady creep rate of the sample as the strain amplitude of vibrations was increased.

4. DISCUSSION

The sensitivity of the steady creep rate of a test sample to superimposed torsional vibrations was thought to have its origin at vacancy-dislocation interactions. The generation-pinning-annihilation-climb model of Feltner[7] for explaining cyclic creep straining was adopted to interpret the present results. The initial decrease in creep rate with the increase in strain amplitude of vibrations might be attributed to a strain hardening effect resulting from the more complex stress and additional slip. The forced glide motion of jogged screw dislocation lines is known[8] to be an important source of vacancy creation. The possible side-motion of the jog together with its forward and backward forced motion under the action of the cyclic stress caused the created vacancies to be distributed around the dislocation line. After passing through the vacancy cloud thus formed, the moving dislocation segment would sweep sufficient number of vacancies and become pinned. The increase in hardening thus effected decreased the average slip distance of the dislocations and caused the observed decrease in creep rate.

As the strain amplitude increased the overcoming of the pinning points became possible. Besides, the pinning effect was not permanent. Individual vacancies were pumped through the dislocation cores to annihilation sites thus giving rise to dislocation climb. This mechanism resulted in the elimination of

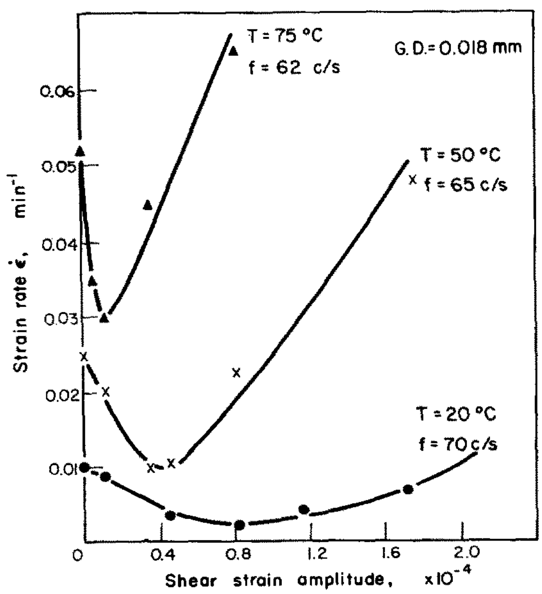

FIG. 3. Dependence of the equilibrium creep rate at different temperatures on the shear strain amplitude of imposed vibrations.

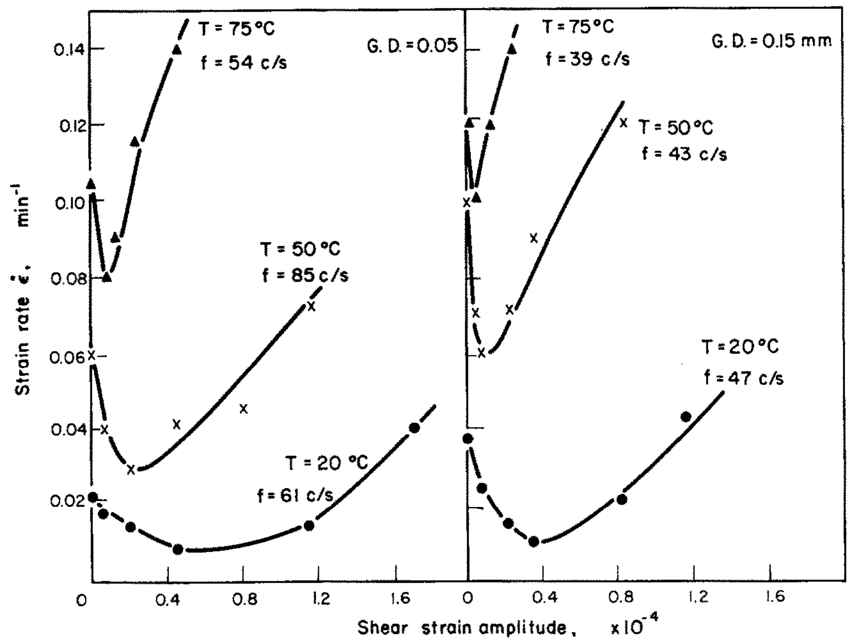

FIG. 4. The effect of temperature and grain size on the position of the minimum creep rate on the strain amplitude axis of the induced vibrations.

pinning atmospheres together with a dislocation climb which would remove the dislocation far enough to escape its permanent obstacle. This view was assisted by the observed increase in the slip distance as indicated by the increased creep rate.

Also, it was plausible to think that the excessive increase at higher frequencies of the creep rate was probably a consequence of the higher average stresses on the specimen. Weertman[9] previously showed that the creep rate goes at about the fourth power of stress. This seemed to be consistent with the greater effect of higher frequency since the specimen would be at the highest stress a greater fraction of time.

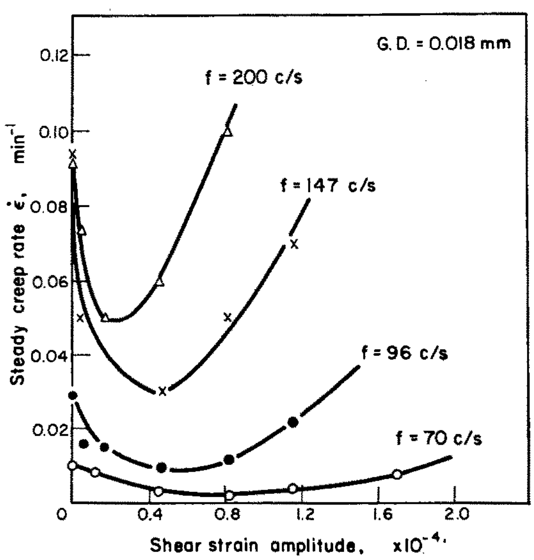

FIG. 5. Steady creep rate dependence on the frequency of the imposed vibrations.

The effect of increase of temperature and grain size on the enhancement of the processes responsible for the observed creep rate variations was explained as follows. The increased thermal energy at high temperatures assisted the glide motion of dislocations thus being able to overcome obstacles such as point defects or Peierls-Nabarro hills. The slip planes in large-grained samples were previously found[10] to be relatively clear from obstacles that hinder dislocation motion. The average slip distance in such samples was thus relatively larger and consequently the observed phenomenon occurred at lower values of strain amplitudes.

Finally, it was also thought that prismatic slip of screw dislocations, which was known[11] to take place in hexagonal structures at relatively high temperatures might take part in the final increase in creep rate. Because of the low crystallographic density of prismatic planes in h.c.p. metals, prismatic slip has a strong Peierls-Nabarro force. At high temperatures thermal agitation together with the applied stress seemed to provide sufficient energy to cause a dislocation segment to cross-slip in a prismatic plane, and thus accelerated the creep rate.

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