EFFECT OF POINT DEFECTS ON MECHANICAL
PROPERTIES OF METALS

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M. Meshii, Principal Investigator
Professor of Materials Science and Engineering

Northwestern University
Evanston, Illinois 60201

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TECHNICAL PROGRESS REPORT FOR THE
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ABSTRACT

The research activities to be reported here can be divided into five sections. A number of reports have been prepared from these research activities. (1) Electron Irradiation Softening in Pure Iron. Some of the results were reported at the U. S.-Japan Seminar on Radiation-Produced Defects and Defect Clusters and Their Effects in Metals, at the International Conference on Fundamental Aspects of Radiation Damage in Metals, and the Spring Meeting of TMS/AIME (COO-1367-63, -66, -67, -72). (2) Effect of Impurities on Electron Irradiation Softening. (3) Electron Microscopic Investigation of Electron Irradiation Softening. The details of this investigation have been reported in a manuscript to be published in Philosophical Magazine. A preprint of this manuscript is attached to this report (COO-1367-64). The results were also presented at the Annual Meeting of EMSA (COO-1367-68). (4) Surface Film Softening. A manuscript (COO-1367-65) has been prepared to report some of the findings. The results were also presented at the Fall Meeting and the Annual Meeting of TMS/AIME (COO-1367-70). (5) Direct and Indirect Studies of Dislocation Motion by Etch Pit Technique and Macroscopic Deformation. The results were reported at the Fall Meeting of TMS/AIME and will also be reported at the Annual Meeting.

1. Electron Irradiation Softening in Pure Iron

The effect of electron irradiation on the activation volume and the activation energy of the plastic deformation of iron single crystals was examined. The plot of the activation volume and the activation energy against the stress clearly showed that both were reduced by the electron irradiation. This is in agreement with the prediction of the theory which we reported earlier [Acta Met. 21, 753 (1973) C00-1367-46]. The observation further supports our contention that the motion of screw dislocations is responsible for the macroscopic yielding and the presence of the irradiation-induced interstitials aids the thermally activated motion of the screw dislocations by assisting the formation of double kinks. Other evidence also strongly and consistently supports the intrinsic mechanism involved in the low temperature strength and its softening in iron.

It is known, however, that the edge dislocations move at a stress level considerably lower than that for the screw dislocation motion. Furthermore, the increase in the mobility of the screw dislocations also promotes the production of the non-screw segments of the dislocations. Therefore the observed softening effect must be due to the combined effect of the increased non-screw density and the increased mobility of the screw dislocations. The experimental evidence indicating the importance of the production of non-screw dislocations has been obtained. Currently, a quantitative method to show this effect is being developed and will be reported along with the experimental evidence.

The annealing of the electron irradiation softening has also been determined. The softening effect disappears during the Stage I recovery and shows a good correspondence to the resistivity recovery.

Some of these results have been discussed in COO-1367-63, -66, -67, and -72. Further details of the experimental results and their analysis are being written up in a manuscript and will be reported in the near future.

2. Effects of Impurities on Electron Irradiation Softening

Some preliminary results indicate that the softening effect is small in impure iron single crystals (Ferrovac E iron grade). The presence of impurities tended to induce a cubic texture in the iron specimens; consequently, single crystal specimens having the tensile orientation for $\chi = 30^\circ$ and $\lambda = 45^\circ \sim 55^\circ$ were rarely produced. Recently, we finally developed a technique which reproduced the [221] orientation crystals. Therefore, these crystals will be used to examine the reproducibility of the above results.

3. Electron Microscopic Investigation of Electron Irradiation Softening

The electron irradiation softening has been explained by an intrinsic mechanism in which the stress field of the irradiation-induced interstitials promotes the double kink formation on screw dislocations, thereby increasing the dislocation mobility. The agreement between the theoretical predictions and the experimental results is the sole basis for accepting the mechanism as the satisfactory explanation for the phenomenon. Therefore it is only prudent to examine the dislocation structures associated with the electron irradiation softening and its orientation dependence. Furthermore, the effect of increased mobility on the generation of non-screw dislocation segments may also be a contributing factor for the observed softening. For this reason, electron microscopic observation was

used extensively. The details of this investigation will be published in Philosophical Magazine. The preprint of this manuscript is COO-1367-64. Some results were also presented at the annual meeting of ASME, COO-1367-68. A brief summary of this investigation is as follows:

- (1) Long, jogged screw dislocations and small dislocation loops dominated the deformation structure.
- (2) The distribution of these dislocations was uniform throughout in the pure iron specimens, with or without the irradiation. However, the specimen which was carburized and quenched showed an uneven distribution of dislocations.
- (3) In all specimens, the significant density of the secondary dislocations was always present, from the earliest stage of deformation examined. In the crystals which were oriented for the hard (112) single slip, the primary and conjugate dislocations were observed to have equal density, while dislocations of all four Burgers vectors were observed in the crystals oriented for the soft ($2\bar{1}1$) single slip.
- (4) The effect of electron irradiation on the deformation structure was not significant ($\epsilon \geq 1.5\%$). This observation is not surprising for the soft ($2\bar{1}1$) crystals; however, it is not expected in the hard (112) crystals in which the irradiation drastically changes the stress-strain curve. The change of dislocation density by several times cannot explain the change in the stress-strain curve. Therefore the present observation suggests that the electron irradiation softening is caused primarily by an increase in dislocation mobility.
- (5) The presence of the secondary dislocations is explained by the large difference in the mobility of edge and screw dislocations in b.c.c. metals at low temperatures.

- (6) The structural difference between the hard (112) and the soft ($2\bar{1}1$) crystals is explained by the Schmid factors for the different slip systems. However, this structural difference does not appear to be the primary cause of the different irradiation effects observed for the two orientations.
- (7) It is suggested that the effect of interstitials can be significantly different depending on how the interstitials are alloyed into the matrix crystal. The irradiation-induced interstitials, which distribute nearly randomly, increase the mobility of the screw dislocations at low temperature. However, the interstitials introduced by the thermal diffusion, tend to segregate at dislocations. The segregated portion of interstitials causes an additional effect, namely, the source pinning. This source pinning is suggested as primarily responsible for the uneven dislocation distribution and the hardening effect observed in the carburized iron at very low temperatures.

4. Surface Film Softening

The effect of surface films on the plastic deformation is well known in fcc metals. The surface films increase the yield stress considerably more than the value expected from the arithmetic addition of the strength due to the cross section of the surface film. On the other hand, the surface film effect on the low temperature strength of bcc metals has been largely ignored until recently. The particular interest in the surface film effect for the present research project arises from the fact that the surface film decreases the yield stress of bcc metals at low temperatures. It is now well established that irradiation (electron and neutron) also reduces the yield stress in the low temperature region.

Similarly, alloying (solid solution) and prestraining also reduces the yield stress. It is interesting to note the common feature in these phenomena; that is, the causes for hardening in soft fcc metals reduce the yield stress of bcc metals at the low temperature range where the high yield stress values result from a large temperature dependence of the yield stress.

In the present study, the surface film effect was studied by Ni-plating iron single crystals. The softening effect was clearly observed due to Ni films at 77° K. The effect was dependent on the tensile axis orientation. The film also increased the ductility of the iron single crystals significantly. Some details of this surface film softening effect are discussed in C00-1367-65 (enclosed with this Technical Report) and are also discussed in C00-1367-70. Further experiments are in progress and will be reported in the next Technical Report. It is hoped that a systematic explanation will be found for the series of the softening phenomena in bcc metals at the low temperature region.

5. Direct and Indirect Studies of Dislocation Motion by Etch Pit Technique and Macroscopic Deformation

Nearly all of the results obtained in the plastic deformation of crystalline materials are customarily analyzed in terms of dislocation motion. In the analyses, the proportionality between strain rate and dislocation velocity is assumed. Considering the extent of such applications of the dislocation theory, it is rather surprising that relatively few attempts have been made to ascertain the proportionality or to examine the relation, particularly under such experimental conditions that the direct comparison of the macroscopic deformation with the motion of indi-

vidual dislocations can be carried out with the least experimental ambiguity.

In the present study, using low dislocation density copper single crystals of the same geometry (10 x 3 x 3 mm), the dislocation velocity measurements and the macroscopic deformation tests were carried out to facilitate the comparison. The specimens were irradiated with 2 MeV electrons at 100° K. Four test temperatures, 4.2°, 25°, 50° and 100° K were chosen to study the temperature effect, and the dislocation velocities were determined over a range from 5×10^{-6} to 3×10^{-1} cm/sec. Some preliminary results were reported in the previous report. The important results are summarized as follows:

(a) At all four test temperatures, the dislocation velocity-stress relation can be expressed well with the relation

$$v = v_0 (\tau / \tau_0)^m,$$

where v and τ are the dislocation velocity and applied stress. v_0 is 1 cm/sec, and τ_0 and m are empirical constants (see Table I).

Table I

Testing Temperature (° K)	τ_0 (g/mm ²)	m	τ_I (g/mm ²)	m^*
4.2	213	59	262	84
25	161	53	220	39
50	125	38	159	39
100	73	58	120	46

τ_I : yield stress after irradiation

m^* : $d \ln \dot{\gamma} / d \ln \tau$

- (b) The stress exponent, m , is large ($\cong 50$) in comparison with $m \cong 1 \sim 2$ for an annealed copper. (The m value for dilute Cu-Ni alloys is reported to be ~ 12 at 77°K).
- (c) The large, positive temperature dependence of the dislocation velocity is noted, suggesting that the thermal activation plays a determining role in the dislocation motion. It should be noted that the relatively small, negative temperature dependence of the dislocation velocity was observed in annealed copper.
- (d) The activation volume and energy can be calculated from the present data for the dislocation motion. Except for the results at 100°K , these parameters can be rationalized by a single activation process. The parameters for 100°K show an anomaly. For example, the activation energy-temperature plot shows a linear relation for the three lower temperatures, while the activation energy obtained at 100°K is about two times larger than the extrapolated value.
- (e) The temperature dependence of the stress giving a constant dislocation velocity, τ_0 for $v = 1 \text{ cm/sec}$, $\tau = \tau_{-3}$ for $v = 10^{-3} \text{ cm/sec}$, $\tau = \tau_{-5}$ for $v = 10^{-5} \text{ cm/sec}$, etc. is similar to the temperature dependence of the yield stress of irradiated copper specimens (cf. τ_I vs. τ_0 in Table I). In particular, when the increment in the yield stress due to the irradiation, $\Delta\tau$, is plotted against temperature, the $\Delta\tau - T$ relation coincides with the $\tau_{-3} - T$ relation.
- (f) The above coincidence can be interpreted as follows: $\Delta\tau$ represents the effective stress component of the flow stress in irradiated copper, while the applied stress is nearly equal to the effective stress when the dislocation velocity is determined. The observation also suggests that the average velocity of dislocation is approximately 10^{-3} cm/sec during macroscopic deformation.

(g) The comparison of m^* with m (Table I) indicates that the stress dependence of the dislocation velocity is well manifested by the stress dependence of the strain rate. Since the difference ($m^* - m$), deviates from zero in both directions, this is most likely due to experimental error. On the other hand, if the difference is attributed solely to the change in the mobile dislocation density, the change is within a factor of 2 - 6.

(h) The activation volumes and energies obtained from the dislocation velocity measurements and the macroscopic deformation are in excellent agreement except for those for 100° K.

(i) The present investigation indicates that the analysis of the macroscopic deformation in terms of dislocation motion is well justified in electron irradiated copper. Similar justification is expected to be held in the effect of electron irradiation in other metals.

(j) The model of macroscopic yielding emerging from the present study is as follows: As the applied stress increases below the macroscopic yield stress, the fraction of dislocations moved decreases, and the average velocity of the dislocations moved can be represented by the empirical equation given earlier. All dislocations in the primary slip systems move and the dislocation multiplication starts to occur before the macroscopic yield point is reached. As the macroscopic yielding takes place, the rapid increase in dislocation density starts to immobilize some dislocations by the mutual trap. At the same time, the internal stress increases so that the quasi-steady state of dislocation motion (10^7 mobile dislocations and 10^{-3} cm/sec average dislocation velocity) is attained after the yielding.

Some of the above results are being reported in C00-1367-69 and C00-1367-71. Two manuscripts are being prepared and will be available shortly.

Reports Resulting from the Present Project

- (1) - (62) COO-1367-1 through COO-1367-62. These reports have been included in the previous Technical Progress Reports.
- (63) "Mechanical Effects of Electron Irradiation in Iron Single Crystals", to be published in the Proceedings of Int'l Conf. on Fundamental Aspects of Radiation Damage in Metals, Gatlinburg, Tenn., October 1975, COO-1367-63.
- (64) "Deformation Structures in Ultrapure Iron", Philosophical Magazine, in press, COO-1367-64.
- (65) "Surface Film Softening in Iron Single Crystals", to be submitted to Scripta Metallurgica, COO-1367-65.
- (66) "Effect of Orientation, Temperature and Strain Rate on Electron Irradiation Softening", Abstract of Talk at Spring Meeting of TMS/AIME, Toronto, May 1975, COO-1367-66.
- (67) "Effects of Annealing and Prior Deformation on Electron Irradiation Softening", Abstract of Talk at Spring Meeting of TMS/AIME, Toronto, May 1975, COO-1367-67.
- (68) "Structure of Deformed Iron: Irradiation Softening and Orientation Dependence", Proceedings of Thirty-Third Annual Meeting of Electron Microscopy Society of America, p. 168, Las Vegas, August 1975, COO-1367-68.
- (69) "Dislocation Motion in Irradiated Copper Single Crystals", Abstract of Talk at Fall Meeting of TMS/AIME, Cincinnati, November 1975, COO-1367-69.
- (70) "Low Temperature Softening Mechanisms in Iron", Abstract of Talk at Fall Meeting of TMS/AIME, Cincinnati, November 1975, COO-1367-70.
- (71) "Comparison of Dislocation Motion with Macroscopic Plastic Deformation in Electron Irradiated Copper", Abstract of Talk at Annual Meeting of AIME, Las Vegas, February 1976, COO-1367-71.
- (72) "Irradiation Softening in Pure Iron Single Crystals", Text of Paper Presented at U.S.-Japan Seminar on Radiation-Produced Defects and Defect Clusters and Their Effects in Metals, co-sponsored by the National Science Foundation and the Japan Society for the Promotion of Science, Ames, Iowa, September 1975, COO-1367-72.
- (73) "Technical Progress Report for the Period from January 1, 1975 to December 31, 1975, submitted to the U. S. Energy Research and Development Administration for Renewal of Contract AT(11-1)1367, COO-1367-73.