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MECHANICAL EFFECTS OF ELECTRON IRRADIATION IN IRON SINGLE CRYSTALS*

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ABSTRACT

Electron irradiation (2 MeV, up to 6 x 10^{18} e/cm^2) decreased the yield stress of iron single crystals in the temperature range from 4.2° to 80° K. The softening effect was highly dependent on the tensile axis orientation. The temperature and strain rate dependency of the yield stress was increased by the irradiation. The annealing of the softening took place between 90° and 150° K. The observation is consistent with an intrinsic solid solution softening mechanism based on the enhancement of screw dislocation motion due to dispersed interstitials.

INTRODUCTION

Low temperature electron irradiation produces a softening effect in iron.[1,2] As the self interstitials are known to interact strongly with dislocations,[3] this softening phenomenon aroused curiosity about the possible mechanisms. It has been reported that low temperature neutron irradiation also causes the softening effect.[2,4]

In this manuscript, the nature of the electron irradiation softening is further investigated by examining the effects of tensile axis orientation, the temperature and strain rate dependence of the yield stress and the effect of post-irradiation annealing. As the deformation

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structures of the irradiated and unirradiated iron specimens were nearly identical,[5] the enhancement of dislocation motion by electron irradiation appears to be primarily responsible for the observed softening. The misfit strain associated with dispersed interstitials exerts a couple force on screw dislocations, enhancing the double kink formation,[6] and can be the cause of the softening. The orientation dependence suggests that the core structure of a screw dislocation and/or the potential variation for the screw dislocation gliding on the different slip planes may also be sensitively altered by the presence of the interstitials.

EXPERIMENTAL RESULTS

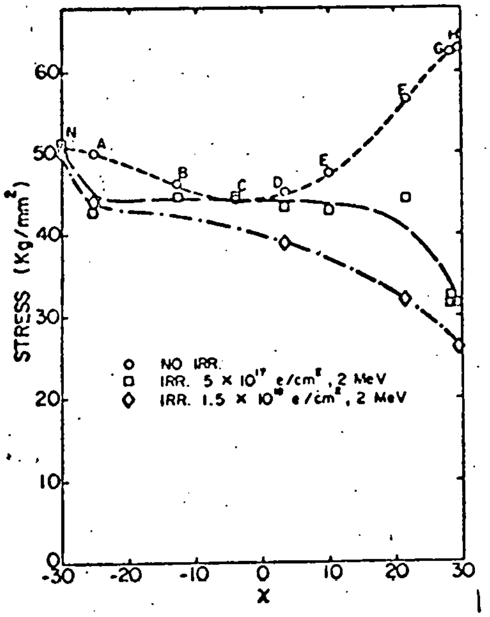
The experimental procedures are detailed in our earlier reports.[1,7] The essential points are: (1) The Battelle-AISI iron containing less than 5 wt. ppm of non-metallic impurities and 30 wt. ppm of metallic impurities was used as the starting material; (2) The single crystal growth and the subsequent annealing were performed in the ZrH_2 purified hydrogen atmosphere; (3) The 2 MeV electron irradiation was carried out below 60° with dosages up to 6.2×10^{18} e/cm^2 (estimated interstitial concentration $\sim$ 100 ppm).

Orientation Dependence

The dependence of the yield stress of bcc metals on the crystallographic orientation of the tensile axis is well known.[8] However, the correlation of this orientation dependence with the effects of solutes, or point defects, has not been investigated except in a few cases.[7] In this investigation two directional parameters, λ and χ, were varied to study the relation of the orientation with the irradiation effect. λ represents the angle between the tensile axis and [110], and was $\sim 10^\circ$ when χ was varied. χ represents the angle between [101] and the normal to the maximum resolved shear stress plane containing the primary Burgers vector, $a/2[11\bar{1}]$. Therefore the maximum resolved shear stress plane coincides with the (211), (101) and (112) planes for $\chi = -30^\circ$, 0° and 30° respectively. The variation of the irradiation softening with χ was striking (Fig. 1). At $\chi \cong 30^\circ$ a large softening effect was observed.

With the dosage of 1.5×10^{18} e/cm^2, the yield stress was reduced by 60%. The resulting yield stress was ~ 25 kg/mm^2 (expressed by the tensile stress) at 60° K, the lowest yield stress ever reported in iron at this temperature range. The irradiation softening effect for $\chi = 0$ was mild, a reduction of yield stress by 10% with similar irradiation. Consequently, the post-irradiation yield stress decreases spontaneously with χ from -30° to 30°.

The effect of λ was examined at $\chi = 30°$ (Fig. 2). The softening effect remained large as λ was increased from 10° to 20°. On the other hand, when λ was reduced slightly from 10°, the magnitude of the softening decreased rapidly and was less than 20% at $\lambda \cong 4°$.



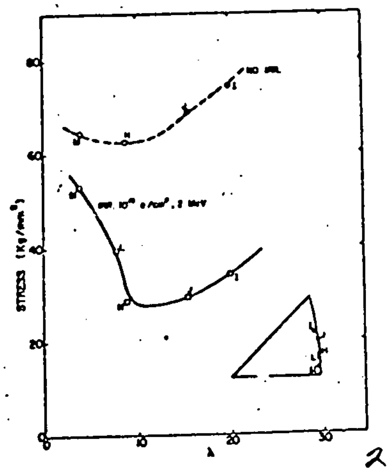


Fig. 1: Yield stress vs. χ relation.

Fig. 2: Yield stress vs. λ relation.

Temperature and Strain Rate Dependence of Yield Stress

The temperature dependence of the yield stress, $\partial\sigma/\sigma T$, was increased by the irradiation in spite of the fact that the magnitude of the yield stress decreased. Therefore the fraction of softening was large between 40° and 80° K (Fig. 3).

Since electron irradiation improved the ductility of the iron, the strain rate dependence could be more reliably determined over the temperature range from 4.2° to 80° K in the irradiated iron (Fig. 4). The irradiation increased the strain rate dependence. The strain rate dependence also increased with the temperature and reached the maximum between 40° and 60° K. It appeared to decrease with a further increase in temperature.

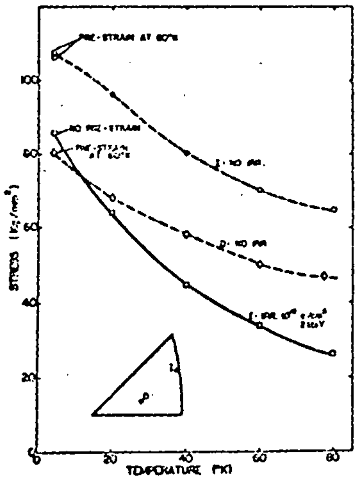


Fig. 3: Yield stress vs. temperature relation. The solid line represents the yield stress of irradiated specimens. The yield stress of unirradiated specimens at 4.2° K was determined after prestrain at 60° K.

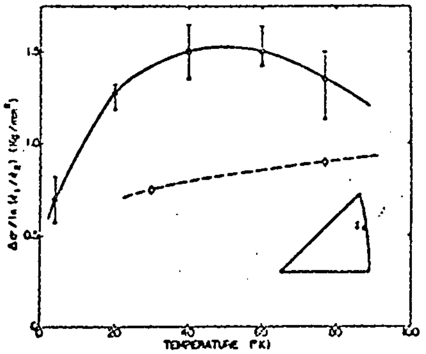


Fig. 4: Strain rate dependence of yield stress vs. temperature dependence. The solid line represents irradiated specimens. The data for unirradiated specimens (open diamond) are not as reliable as those of irradiated specimens, as the specimens failed before a number of strain rate changes could be carried out.

Recovery of Irradiation Softening

When the irradiated iron specimens were annealed at a temperature above 90° K, the softening effect was reduced (Fig. 5). This recovery peak of the irradiation softening centered around 105° K and the recovery effect appeared to saturate near 150° K.

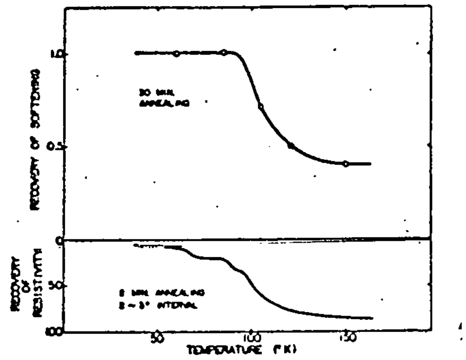


Fig. 5: Isochronal recovery of electron irradiation softening and irradiation induced resistivity.

DISCUSSION

The resistivity recovery of electron irradiated iron indicates that no free migration of interstitials takes place below 100° K.[9] The dislocation-interstitial interaction is considerably larger than the dislocation-vacancy interaction.[10] As the interactions can be regarded as primarily elastic in nature, a similar situation should exist in bcc metals. Therefore the softening effect is caused by the interstitials of nearly random distribution. According to an electron microscopic investigation[5] of the dislocation structure in irradiated and unirradiated iron single crystals after deformation at 60° K, there was little difference in structure between the two types of specimens. In both cases, screw dislocations were uniformly distributed throughout the specimens. This structural observation supports a softening mechanism due to an increase in dislocation mobility. A theory has been proposed[6] to explain an increase in dislocation mobility by point defects. The formation of double kink is promoted by a local misfit strain, since its stress field exerts a couple force on a screw dislocation. The apparent activation volumes and energies can be calculated from the temperature and strain rate dependence of the yield stress. These quantities were clearly reduced by electron irradiation, supporting the contention that the dislocation motion is aided by the interstitials.

The mechanism of the electron irradiation softening strongly supports the intrinsic mechanism for the low temperature strength of iron and suggests a mechanism for the solid solution softening phenomenon. On the other hand, an extrinsic mechanism such as gettering of carbon and nitrogen atoms in iron by titanium (scavenging mechanism) has been reasonably well established.[11] It has also been proposed in a series of recent investigations in niobium and tantalum base alloys that the solid solution softening effect occurs exclusively in ternary systems and that the softening effect is attributed to the effect of the solute-solute interaction on dislocation motion.[12,13] Therefore the possibility of the extrinsic mechanism for the observed irradiation softening must be examined carefully.

The interstitial impurity content of the specimens used in this study does not favor the extrinsic possibility. The softening effect also decreased with increasing impurity content. The disappearance of the softening effect at the temperature range where the free migration of interstitials occurs also discourages the extrinsic possibility. Another experiment supports this conclusion. The electron irradiation increased the microyield stress (determined as 10^{-4} plastic strain) although the macroyield stress was reduced. If the irradiation is to reduce the resistance of the impurities to dislocation motion, it is difficult to explain the hardening effect on the microyielding. However, the intrinsic mechanism proposed in this report provides a logical explanation for this seemingly contradictory observation.[14] The orientation dependence of the electron irradiation softening effect also supports the intrinsic mechanism. The orientation dependence of the yield stress of pure bcc metals can be understood by the asymmetric core structure of screw dislocations or by the asymmetric distribution of the potential for the dislocation motion to different directions. The core configuration or the potential distribution is expected to be extremely sensitive to the local atomic disturbance (or the local strain field). The presence of interstitial atoms would change the atomic arrangement significantly and may cause the observed orientation dependence of the softening effect.

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