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ROLE OF FRICTION AND SOURCE HARDENING IN DSA AND RADIATION EMBRITTLEMENT OF FERRITIC STEELS AND IRON

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ABSTRACT

It is now well established that dynamic strain aging due to the interaction of the interstitial impurities (IIAs) such as carbon and nitrogen with dislocations leads to decreased ductility as well as energy to fracture. In this study, we report further evidence of such interactions between IIAs and radiation-induced defects in both bainitic steel (A516Gr70) and a martensitic steel (A354) following radiation exposure of tensile and 3-point bend samples to a fast neutron flux. In addition, the hardening components comprising the yield stress, namely the friction and source hardening terms which relate to the resistance to dislocation motion due to the forest dislocations and the locking of the dislocation sources by IIAs respectively were derived. The significance of the radiation effect on the source hardening lies in the fact that the change in this term with neutron radiation flux could dictate the change in the DBTT following irradiation.

The effects of dynamic strain aging and neutron irradiation on the mechanical and fracture characteristics were also investigated in relatively pure (Armco) iron using tensile and 3-point bend fracture tests. The tests were performed as a function of the test temperature and the applied strain-rate and were aimed at characterizing the synergistic effects of interstitial impurities and radiation induced defects. Contrary to the observations of the reduced fracture energy in the DSA region for ferritic steels, *increased* fracture energies are noted in Armco iron apparently due to the increased rates of work-hardening during DSA. These differences were attributed to the absence of precipitates in Armco iron. The friction and source hardening terms are determined directly from the grain size dependence of the yield stress.

1 INTRODUCTION

Dynamic strain aging is distinctly noted in ferritic steels due to the interaction of interstitial impurity atoms (IIAs) such as C and N with dislocations leading to jerky or serrated stress-strain curves which result in a loss of ductility. The IIAs are quite mobile at the irradiation temperature and thus migrate to the point defects that are induced by neutron irradiation thereby resulting in reduced interaction with the dislocations [Wechsler and Murty 1989]. The yield point and degree of serrated flow get reduced following neutron radiation exposure. Low alloy mild steels are commonly used for pressure boundary applications as well as reactor supports in various power reactors and the exposure of these materials to high energy neutrons leads to increased DBTT and decreased toughness; this phenomenon is referred to as radiation embrittlement of ferritic steels.

The extensive data base on various reactor vessel surveillance capsule programs revealed the influence of alloying elements such as Cu, Ni and P on the changes in DBTT and upper shelf energy along with the superimposed effects of radiation fluence and irradiation temperature [Murty 1985]. While the underlying micro-mechanisms responsible for these changes are not exactly clear the analyses implies that elements such as Cu, Ni and P modify the kinetics of carbide precipitation thereby indirectly influencing the radiation embrittlement. These findings suggest that an extensive study is warranted to study the effects of IIAs and various alloying elements on the mechanical and fracture characteristics along with the superimposed effects of radiation. For an understanding of the underlying mechanisms, relatively pure Armco-iron and silicon-killed mild steel [Murty and Hall 1976] are used along with a number of low alloy steels with varied compositions. We present here the experimental results on the mild steels A516Gr70 and A354, typically used for reactor supports, and Armco-iron of varying grain sizes (50-300μm). The degree of serrations and its effects on the mechanical and fracture characteristics are sensitive to the composition of the steel, and these behaviors are examined in these steels.

Tensile and 3-point bend tests were performed to determine the mechanical and fracture properties of the steels. In the mild steels distinct drops in the toughness were noted in the upper shelf region where DSA is apparent, whereas the tests on Armco-iron revealed opposite trends; this is due to the absence of carbides in the Armco-iron. The superimposed effect of neutron radiation exposure on the DSA clearly indicates reduced concentrations of IIAs found in solution thereby increasing the critical temperature for DSA. A reduced temperature range of serrated flow was also noted. Synergistic effects of IIAs and radiation-produced defects lead to distinct increases in both the strength and ductility in the DSA regime of unirradiated materials; in particular, dramatic increases in strength and ductility were observed following radiation exposure for the reactor support steel, A516Gr70. Similar effects were noted for A354 but to a much smaller degree.

2 EXPERIMENTAL ASPECTS

Table 1 lists the compositions of the iron and steels investigated here. Both the tensile and 3-point bend samples were prepared from the forged plates of A516Gr70 and A354 taken at the 1/4-thickness. Armco iron with varied grain sizes was provided by the Defense Metallurgical Research Laboratory, India in plate form. The A516, A354 and Armco iron samples were exposed in the PULSTAR reactor at NCSU to a fast neutron fluence of ~2×10^{18} n/cm^2 at an operating temperature of 50°C. The flux measurements were made using high purity nickel wires which were inserted in the radiation capsule along with the samples. The nickel wires upon bombardment with high energy neutrons undergo an (n,p) reaction which forms the unstable isotope ^{58}Co which in turn decays by emitting a signature 811 keV gamma ray. A NaI detector was used to measure the activity of the nickel wire thereby determining the sample fluence.

Table 1. Compositions (wt%) of Ferritic Steels

Material	C	Mn	Si	S	P	Cu	Mo	Al	Ni	Cr	V
A516Gr70	0.20	0.98	0.20	0.018	.024	0.24	0.03	0.018	0.16	0.20	0.004
A354	0.55	1.65	0.60	0.04	0.04	0.60	-	3.99	-	3.99	-
Armco-Fe	0.008	0.04	0.02	0.003	0.004	-	-	-	-	-	-

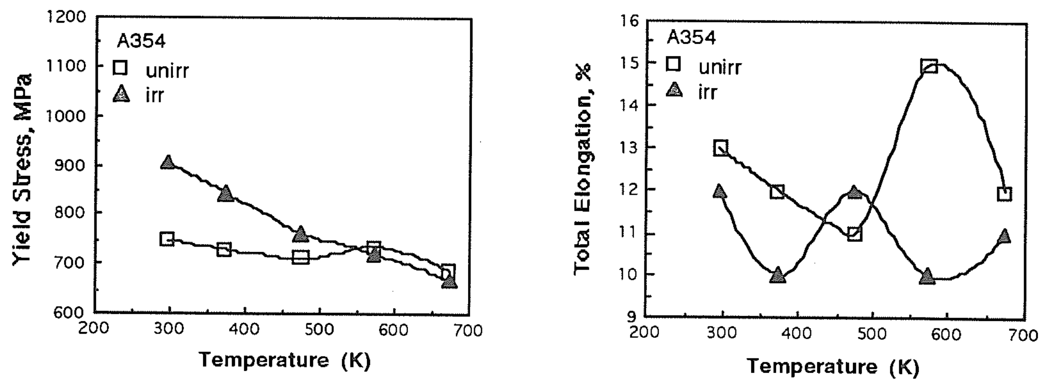
Tensile and 3-point bend tests were performed on a closed loop Instron testing machine. Three-point bend tests were made using a compression jig which transforms a tensile load applied to its ends into a compressive load onto a v-notch specimen supported at three points. Load and load-line displacements were recorded. Areas under the load-displacement curves up to the maximum load are taken to be a measure of the fracture initiation energy, E_1, while that after maximum load to fracture gives fracture propagation energy, E_2, so that the total energy is the sum of the two.

3 EXPERIMENTAL RESULTS AND DISCUSSION

Tensile and 3-point bend tests were performed on unirradiated and irradiated steel specimens and here we emphasize results on A354 steel while details on A516 may be found in a recent study by

Hong and Murty [1992]. The load versus elongation curves obtained in tensile tests of unirradiated and irradiated A516Gr70 and A354 steels at various test temperatures (to 673K) reveal distinct differences due apparently to differing microconstituents (ferrite with some bainite in A516 versus martensitic structure in A354). Luders bands and serrations are noted in both unirradiated and irradiated A516 steel while A354 steel exhibited smooth transition from elastic to plastic regimes. Neutron radiation exposure of A516 steel resulted in decreased dynamic strain aging (DSA) which manifested in very small load drops in the tensile curves. Both of these effects are not as distinct as those reported in a silicon killed mild steel [Murty and Hall 1976] although these are quite similar to those observed in A533 pressure vessel steel [Jung and Murty 1987]. The reduced DSA effect following radiation exposure is again according to the earlier reports on different steels [Murty 1985 & Wechsler and Murty 1989]. The effect of neutron irradiation is rather minor in A354 steel except for slight hardening accompanied by reduced strain-hardening at low temperatures. At temperatures above about 573K, *in-situ* annealing of radiation damage is noted (see later).

The temperature variations of the yield stress and total elongation to fracture are depicted in Figures 1a and 1b respectively for A354 steel; results on A516 were reported by Hong and Murty [1992]. Radiation hardening resulted in increased yield strength at temperatures below about 500K while little effect of neutron radiation exposure is noted at higher temperatures (Fig. 1a). Decreased elongations representing radiation embrittlement is noted (Fig. 1b) at all test temperatures except at 500K where essentially no change (or a slight increase if at all) is seen. The dip in ductility at this temperature in the unirradiated material suggests the existence of DSA albeit no load drops are visible in the stress-strain curves; these ductility dips have been clearly identified in various mild steels including A516 [Hong and Murty 1992].



(a) Figure 1 (b)

Temperature Variation of Yield Stress and Elongation

The yield stress may be regarded as composed of 2 terms, the friction (σ_i) and source hardening (σ_s) [Murty and Oh 1983] where,

$$\sigma_y = \sigma_i + \sigma_s . \tag{1}$$

The source hardening arises from the locking of the dislocation sources by impurities, defects etc., and the friction hardening term represents the resistance to the gliding dislocations, once they are freed from the locked sources. The source hardening is essentially zero for fcc metals which thus exhibit *rounded* yield, while it is large enough in bcc metals to produce distinct Luders bands. Exposure to high energy neutrons results in increased dislocation density along with other defects such as depleted zones, and the formation of new precipitates. The friction hardening thus increases with fluence [Murty and Oh 1983],

$$\sigma_i = \alpha G b \sqrt{\phi t} = \alpha G b \sqrt{\Phi} , \tag{2}$$

where G is the shear modulus, b is the Burgers vector, ϕ is the neutron flux, t is the irradiation time, Φ is the neutron fluence and α is a geometric factor of about unity. In fcc metals the neutron radiation exposure is expected to increase σ_S since radiation-induced defects migrate to the dislocation sources during irradiation and lock them. Because the source hardening is negligible for unirradiated fcc metals, the increase in σ_S results in observed yield points after irradiation. BCC metals and steels are different in that the yield points exist even prior to irradiation due to the locking of the dislocation sources by the IIAs. Neutron radiation exposure at temperatures of the order of 325K and higher result in the migration of carbon and nitrogen from the matrix as well as solute atmospheres to the radiation produced vacancies and their complexes [Murty 1985]. This should then result in a decrease in σ_S as reported by Murty and Oh [1983] and is commonly noted in decreased yield points in irradiated steels.

The stress-strain curves were used to calculate the two hardening terms from an extrapolation of the work-hardening region to the elastic line, the intersection point of which is the friction hardening; in addition, the difference between the lower yield stress and the friction hardening is the source hardening. Figure 2 depicts the temperature variations of these hardening terms before and after neutron radiation exposure for A354 steel. The absence of yield points and Luders bands resulted in no source hardening term. The friction hardening was equal to the yield stress (Fig. 1a) and exhibited increased values at low (≤500K) temperatures according to Eq.1; a similar trend is noted in the friction hardening for A516 also while the source hardening decreased following neutron irradiation (Figure 3). At temperatures above about 500K, the yield stress was completely comprised of friction hardening similar to A354 which is again a reflection of the absence of yield points (or decreased concentrations of IIAs in solution) at these temperatures following neutron irradiation. These complex trends in the temperature and radiation effects on the source hardening clearly depict the synergistic influences of DSA and radiation-induced defect complexes on the mechanical properties.

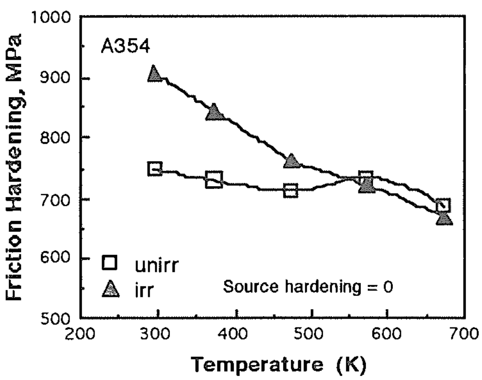


Figure 2

Temperature Variation of Friction Hardening

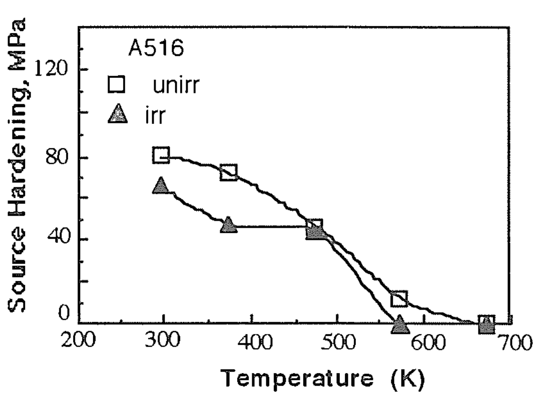


Figure 3

Temperature Variation of Source Hardening

The significance of these findings lies in the fact that the temperature and fluence variations of the friction and source hardening terms find application in predicting the change in DBTT in Cottrell brittle fracture theory. Accordingly,

$$d(\sigma_y k_y) = d(\sigma_y \sigma_s) = 0, \tag{3}$$

so that,

$$\Delta DBTT = -\frac{1 + \dfrac{2\Phi^2 \sigma_y}{\sigma_i}\left(\dfrac{\partial \sigma_s}{\partial \Phi}\right)}{\left(1 + \dfrac{\sigma_y}{\sigma_s}\right)\left(\dfrac{\partial \sigma_s}{\partial T}\right)} \Delta\sigma_i . \tag{4}$$

Thus an estimation of the change in the transition temperature with neutron fluence requires a knowledge of the fluence variations of both σ_i and σ_s. Work is underway to investigate these components following different fluences so that the above equation may be applied to predict the changes in the transition temperatures.

3-point bend tests were performed on unirradiated and irradiated samples over the test temperature range from ambient to 673K. From these data the effect of the test temperature on the energy to fracture was determined (Figures 4a and 4b for A516 and A354 steels respectively). The fracture energy for A516 (Fig. 4a) exhibits a dip between 373K and 673K which is the temperature range of DSA. Note that this is the upper shelf regime where temperature independent fracture energy is noted in Charpy tests which is the result of the fast strain-rates and thus the effects of DSA are not discernible. Neutron irradiation resulted in a decrease in the fracture energy as seen in the temperatures below 373K whereas the energy values were higher at 473K and 573K where the unirradiated material exhibits DSA. Thus the 3-point bend test results show good agreement with those noted earlier in the smooth-bar tensile tests. Normal radiation embrittlement is noted at higher temperatures where DSA is distinctly absent. Whereas, the data on A354 as depicted in Fig. 4b revealed a slight increase in fracture energy at lower temperatures and similar amount of decrease at higher ($\geq$550K) temperatures albeit these changes are very small and fall in the experimental uncertainty.

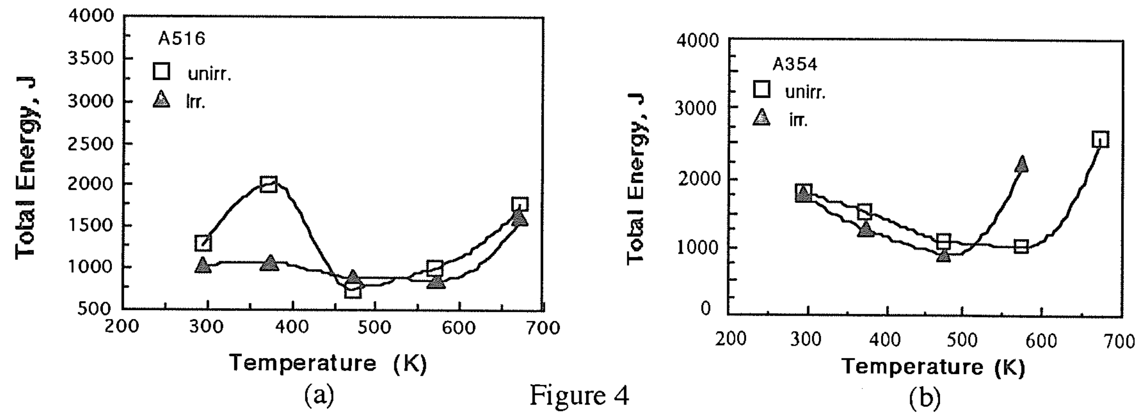


Figure 4

Fracture Energy versus Temperature for A516 and A354 Steels

The superimposed effects of IIAs and radiation-induced defect complexes on fracture energies are also revealed in the tensile tests from which the energy to fracture (toughness J) was estimated from the areas under the true stress versus strain curves. The temperature variations of toughness (J) for both unirradiated and irradiated A516 steel revealed distinct synergistic effects of DSA and radiation while the trends are rather complex in A354 similar to the fracture energies in figure 4b. These results clearly demonstrate the usefulness of tensile tests in assessing the radiation embrittlement of steels in addition to yielding other information such as the source hardening etc.

Tensile tests were performed on Armco-Fe with different grain sizes which gives a direct comparison of the friction and source hardening terms using the Hall-Petch relation. Hong and Murty [1992] investigated the effect of grain size on the yield stress for unirradiated and irradiated Armco-Fe using Hall-Petch plots and their results clearly demonstrated the validity of the extrapolation method. Neutron radiation exposure resulted in reduced yield stress slope implying a decrease in the source hardening term as in the case of mild steels. Figures 5a and 5b are compilations of the load versus elongation curves for material with 180μm grain size before and after irradiation. We note distinct load drops characteristic of type-B serrations at intermediate temperatures in both the as heat treated and irradiated conditions except for the fact that the size of serrations decreased by more than 50% following neutron radiation exposure (see curves at 473K). This feature is akin to that reported in Si-killed mild steel as well as low-alloy steels.

The effects of neutron irradiation on the temperature variation of the friction and source hardening terms followed essentially same trends as in smaller (50μm) grain size material [Hong and Murty 1992]. An increase in the friction hardening following irradiation was noted except at the highest temperature of 673K where annealing may have resulted in little radiation hardening. The source hardening for the unirradiated material exhibits a peak (albeit small) in the temperature range of DSA; however, following irradiation the source hardening decreased and attained a negligible value at the higher temperatures. Exposures to different fluences are now underway to characterize the fluence dependencies of the source and friction hardening terms which are needed for an evaluation of the change in DBTT (Eq.4). More interestingly, the DSA effect was seen to be beneficial in Armco-Fe in contrast to mild and low-alloy steels where DSA resulted in dips in fracture energies in the upper-shelf region due mainly to the presence of carbide and other precipitates which were absent in precipitate-free Armco-Fe [Hong and Murty 1992].

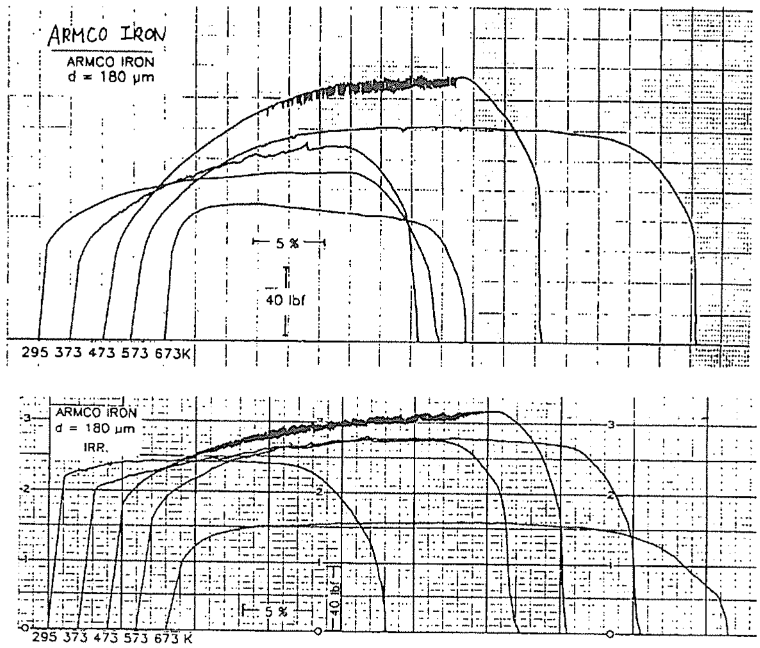


Figure 5

σ - ε Curves for Armco-Fe (d=180μm) Before (a, top) and After (b, bottom) Neutron Irradiation

4 ACKNOWLEDGMENTS

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5 REFERENCES

Hong, J.H. and Murty, K.L. 1992, Effect of Dynamic Strain Aging and Neutron Irradiation on Fracture Characteristics of Various Steels and Iron. Symposium on Microstructures and Mechanical Properties of Aging Material, TMS-AIME Fall Meeting: in print.

Murty, K.L. 1985. Interstitial-impurity Radiation-Defect Interactions in Ferritic Steels. J. Met. October: 34-39.

Murty, K.L. and Hall, E.O. 1976. Dynamic Strain Aging and Neutron Irradiation in Mild Steel. ASTM STP 611: 53-71.

Murty, K.L. and Oh, D.J. 1983. Friction and Source Hardening in Irradiated Mild Steel. Scripta Met. Vol. 17: 317-320.

Wechsler, M.S. and Murty, K.L. 1989. Impurity-Defect Interactions and Radiation Hardening and Embrittlement in BCC Metals. Met. Trans. Vol. 20A: 2637-2649.