SYNERGISTIC EFFECTS OF DYNAMIC STRAIN-AGING AND NEUTRON IRRADIATION ON STRENGTH AND DUCTILITY OF MILD STEEL

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ABSTRACT

Effects of dynamic strain-aging and neutron irradiation on strength and ductility of mild steel are studied at temperatures up to 553K and fluences up to 10^{19} neutrons cm^{-2}. Due to the synergistic effect of dynamic strain-aging and radiation produced defects the strength and ductility were improved following irradiation at intermediate test temperatures (from 373K to 453K). Irradiation flux and test temperature dependences of mechanical properties of mild steel are described.

KEYWORDS

Steel; tensile strength; ductility; neutron irradiation; interstitial impurities; point defects; dynamic strain-aging; work-hardening.

INTRODUCTION

The influence of interstitial impurities on the mechanical properties of steels has been well recognized through the so-called dynamic strain-aging or blue brittle behavior leading to decreased tensile ductility and notched-impact resistance. Similarly, the effect of irradiation induced defects such as vacancies and interstitials on the mechanical properties of metals has been well documented in the literature. The significance of interactions between extrinsic impurities and radiation produced defects is beginning to be recognized (Murty and Hall, 1976; Wechsler, 1979). The interaction of interstitial impurities such as C and N with point and line defects in steels is one such example and these interactions lead to synergistic effects of radiation damage and dynamic strain-aging on the mechanical properties. These interactions between impurities and intrinsic defects can have practical significance such as in the critical role played by residual copper on notch-impact properties of reactor pressure vessel steels (Wechsler, 1979; Steele, 1983).

The interstitial impurities such as carbon and nitrogen play a major role in radiation hardening and strain-aging phenomena (Hall, 1970). Earlier work (Hall, 1962; Little and Harries, 1969; McLennan and Hall, 1963) clearly indicated that these interstitial impurities combine with irradiation induced point defects, such as vacancies and interstitials, either individual defects or loops, to form complexes. These complexes may probably be responsible for part of the hardening (Hall, 1962). At the same time, the creation of these complexes results in reduced net concentration of interstitial atoms in solution (McLennan and Hall, 1963) and thus the irradiated steel becomes non-aging at sufficiently high neutron doses. Earlier work by Murty and Hall (1976) clearly indicated that with increasing fluence, the degree of locking of the dislocations by the interstitial impurities decreased, the critical temperature for onset of serrations increased and the temperature range of blue brittle behavior narrowed, ultimately resulting in a non-aging steel at the highest dose. The suppression of dynamic strain-aging due to neutron irradiation is thus expected to reduce the effect of blue brittleness on the mechanical properties of steels. The major objective of the present study is to uncover these competing effects and the mechanical properties of mild steel (0.05w/o C) are described at various temperatures following neutron irradiation at doses ranging from $\sim 4\times10^{16}$ neutrons cm^{-2} to $\sim 10^{19}$ neutrons cm^{-2}. Test temperatures were varied from ambient to ~553K.

EXPERIMENTAL DETAILS

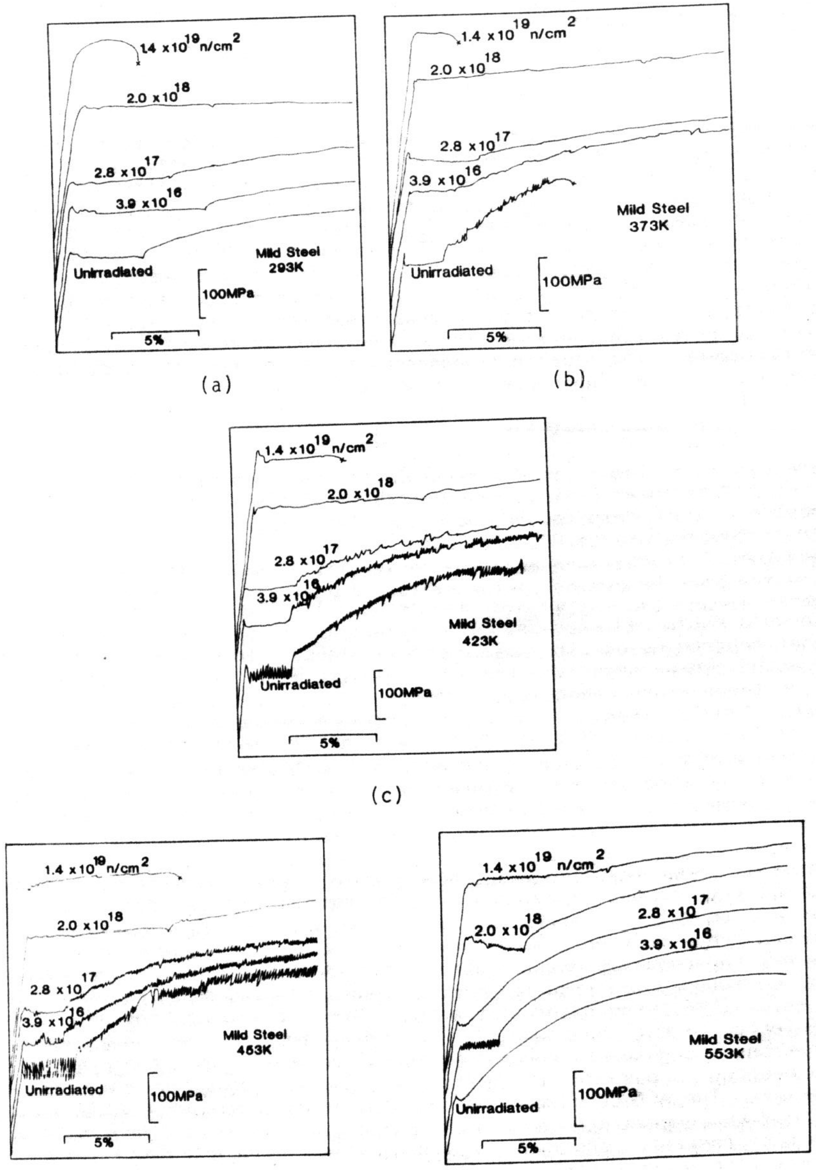
Mild steel wires of 0.001m diameter and 0.0385m gage length were used. The main advantage of wires is that the relatively small volume of the specimens reduced the decay time of γ-activity accumulated during irradiation. The material used was cold-drawn rimmed mild steel whose composition is given in Table 1. The specimens were annealed in vacuo at 973K and the final grain size was 0.038mm (ASTM 6-7).

TABLE 1. Composition of Steel Wires (w/o)

C - 0.050	Si - <0.001	Mn - 0.390	Cu - 0.091
N - 0.004	Al - 0.002	S - 0.012	Sn - 0.003
O - 0.012	Ni - 0.032	Cr - 0.041	Fe - remainder

The prepared specimens were irradiated in the Australian Atomic Energy reactor (HIFAR), the heavy water moderated reactor at Lucas Heights. Different total neutron doses were obtained by insertion in the vertical holes at positions close to the fuel plates for high doses and at positions away from the plates for lower doses. In all cases, the time of exposure was kept essentially constant, and thus the different integrated fluences were obtained by differing neutron dose rates. The fission neutron fluxes were calculated from the γ-activity of ^{46}Ti wire monitors placed near the specimen cans, and four different fluences were obtained: 3.9×10^{16}, 2.8×10^{17}, 2.0×10^{18}, and 1.4×10^{19} neutrons cm^{-2} (>1MeV). The quoted values for the fluences are the average values, and typically the minimum and maximum values of fluxes differed by a factor of ~3 over the length of the specimens. Special precautions were taken to reduce γ-heating of the specimens and the irradiation temperature was 353K, the heavy-water temperature (Hall, 1962).

All of the mechanical tests were performed on a 'hard' tensile testing machine at a crosshead speed of 5.2×10^{-6} m/s which corresponds to a strain-rate of $\sim 1.36\times10^{-4}\ s^{-1}$. The desired temperatures were attained by immersing the



(a) (b) (c) (d) (e)

Fig. 1. Effect of Neutron Fluence on Stress-Strain Curves of Mild Steel at 293K(a), 373K(b), 423K(c), 453K(d) and 553K(e)

specimen and holder assembly in an electrically heated stirred oil or salt bath, and the temperatures were controlled to ±1K.

RESULTS AND DISCUSSION

The effect of neutron radiation exposure on the characteristics of dynamic strain-aging in mild steel was already described in detail by Murty and Hall (1976). We are here concerned primarily with the influence of radiation and dynamic strain-aging on strength and ductility. The effect of neutron fluence on the stress-strain curves of mild steel at selected temperatures is depicted in Fig. 1. At ambient temperature, smooth stress-strain curves were noted with radiation hardening and embrittlement at high fluences. In addition, the rate of work-hardening decreased while the Lüders strain increased with increasing neutron fluence; at the highest fluence, fracture occurred during Lüders propagation resulting in pronounced embrittlement. The fluence dependence on the lower yield stress (σ_{LY}) followed 1/3rd law as shown earlier by Murty (1983):

$$\sigma_{LY} = \sigma_0 + A(\phi t)^{1/3}, \quad (1)$$

where σ_0 is the lower yield stress of the unirradiated material. Fig. 2 is a plot of the lower yield strength versus $(\phi t)^{1/3}$ and shows the linear dependence at room temperature and 373K. The value of A decreased from 91.7 at room temperature to 88.4 at 373K, with stress in Pa and fluence in neutrons cm^{-2}. At these temperatures essentially smooth Lüders bands are noted while the work hardening region exhibited jerky flow in the unirradiated and lightly irradiated (~3.9x10^{16} neutrons cm^{-2}) specimens. At 423K, these two materials exhibited serrated Lüders bands unlike specimens irradiated to higher neutron doses with smooth Lüders bands. Since dynamic strain-aging is characterized by negative strain-rate sensitivity, either a peak or plateau in the temperature dependence of the yield stress is expected (van den Beukel, 1983). Thus, a plot of the fluence dependence of the yield stress at 423K does not follow the 1/3rd law. At 553K, while the unirradiated material exhibited no Lüders propagation with essentially smooth stress-strain curve, specimens irradiated to fluences greater than ~10^{18} neutrons cm^{-2} deformed with jerky Lüders bands. Thus, the functional dependence of the yield stress on neutron fluence was complex at this temperature also.

It is well known that the onset of unstable flow is characterized by a precipitous drop in ductility, as is clear from the stress-strain curves of unirradiated material at ~373K. It is also well established that radiation exposure leads to embrittlement as seen in Fig. 1 (room-temperature data). However, the combination of neutron irradiation and dynamic strain-aging leads to interesting results (Murty, 1984a). As was shown earlier (Murty and Hall, 1976), the onset of serrated flow is delayed following neutron irradiation; i.e., the lower critical temperature for the appearance of serrations increases as neutron fluence increases. Thus, the dynamic strain-aging is observed at relatively higher temperatures in irradiated material. The effect of neutron irradiation on total elongation is plotted at the five temperatures in Fig. 3a which clearly depicts the synergistic effect of radiation and dynamic strain-aging. While the ductility decreased rapidly with neutron fluence (>10^{17} neutrons cm^{-2}) at ambient temperature, it was not affected at other temperatures with the exception of the highly irradiated material. Indeed, as shown by Murty (1984b), total elongation slightly <u>increased</u> with fluence up to ~10^{18} n/cm^2 at temperatures ranging

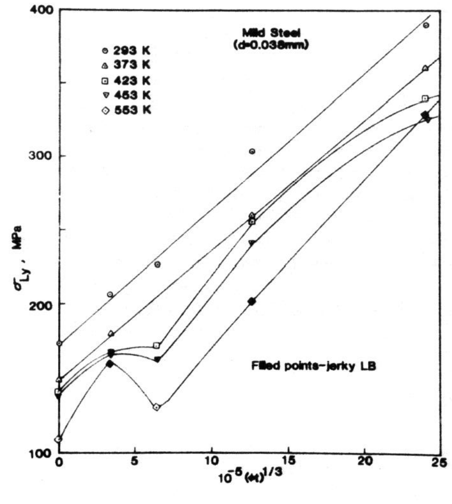


Fig. 2. Fluence Dependence of Lower Yield Stress at Various Test Temperatures

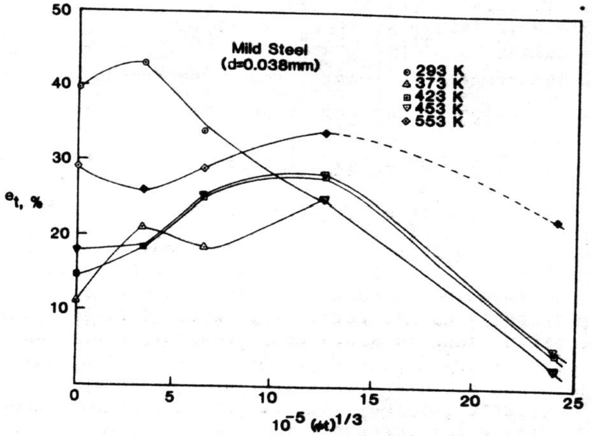


Fig. 3a. Total Elongation Versus Cube-Root of Neutron Fluence

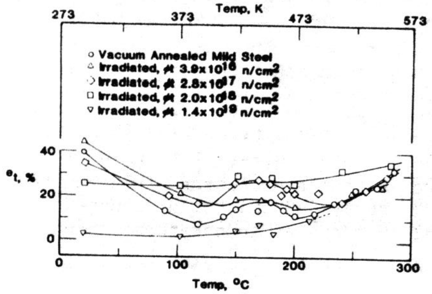


Fig. 3b. Temperature Dependence of Ductility at Various Neutron Fluences

from 373K to 453K. The lack of severe embrittlement at 553K even at the highest fluence of 10^{19} n/cm^2 is believed to be due to in-situ annealing of the radiation damage during the heat up and tensile testing. The temperature dependence of total elongation of the unirradiated and irradiated materials is depicted in Fig. 3b. Distinct ductility minima are noted in the unirradiated and lightly irradiated (to ~10^{16} neutrons cm^{-2}) materials at the lower and upper critical temperatures, respectively, corresponding to the appearance and disappearance of unstable flow. Correspondingly, changes in the Lüders strain are also observed as a function of the test temperature and neutron irradiation. Minima in the Lüders strain are observed at the lower critical temperatures (Murty and Hall, 1976), and from the temperature dependence of the Lüders strain for the material irradiated to the highest fluence it was concluded that at this fluence the specimens failed during Lüders propagation itself with severe localized deformation (Murty and Oh, 1983).

GENERAL DISCUSSION AND CONCLUSIONS

Present study on the temperature dependence of the strength and ductility of neutron irradiated mild steel clearly revealed the synergistic effects of dynamic strain-aging and irradiation produced defects. At elevated temperatures where dynamic strain-aging is observed the lower yield stress and ductility varied with fluence in a complex way, and radiation was not always detrimental to the ductility of the steel. At low temperatures where essentially smooth Lüders bands are noted the lower yield stress increased as fluence raised to 1/3rd power. If the yield stress is regarded as comprised of two components, namely source hardening (σ_s) and friction hardening (σ_f),

$$\sigma_{LY} = \sigma_s + \sigma_f, \tag{2}$$

we find that (Murty and Oh, 1983),

$$\sigma_f = \sigma_f^0 + B\sqrt{\phi t}. \tag{3}$$

Here the source hardening is the stress needed to unlock pinned dislocations and the friction stress is the resistance experienced by these free dislocations in moving through the lattice. The square-root dependence of the friction stress is believed to arise from the long-range forces due to forest dislocations and short-range interactions due to depleted zones produced following neutron exposure by assuming that the density of dislocations and depleted zones increases linearly with fluence. At the same time, the creation of these defects and defect complexes attract the interstitial impurity atoms thereby reducing their concentration in solution available for locking and this results in a reduction of the source hardening (σ_s). This decrease in the source hardening following neutron radiation was responsible for a relatively weaker (cube root) fluence dependence of the yield stress (Eq. 1).

It is interesting to note that Lüders strain at room temperature increases with cube root of fluence similar to the yield stress (Murty and Oh, 1983). This is predicted from the fact that Lüders strain varies linearly with the yield stress for mild steel (Cibois, Lemaire and Weis, 1963). The increase in Lüders strain along with the corresponding decrease in source hardening in irradiated steels implies that the rate of work-hardening should decrease as neutron fluence increases. Indeed, as shown in Fig. 4, the room-temperature work-hardening exponent (m) decreased from ~0.34 for unirradiated to 0.19 at a neutron fluence of 2x10^{18} neutrons cm^{-2}. At elevated temperatures, the intervening effect of dynamic strain-aging resulted in complex functional dependence of m on neutron fluence (Murty, 1984c).

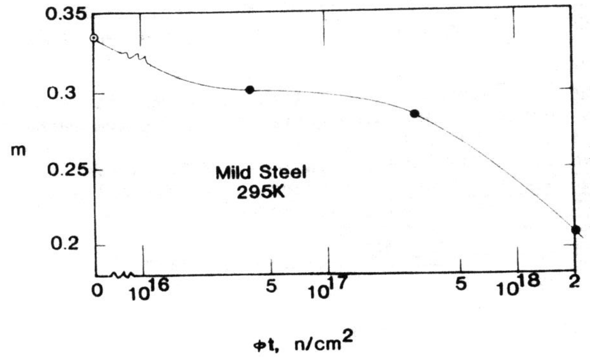


Fig. 4. Fluence Dependence of Work-Hardening Parameter (m) at Room Temperature

The most interesting observation of the present study is the synergistic effect of dynamic strain-aging and radiation damage resulting in simultaneous increases in elevated temperature yield strength and ductility following neutron radiation exposure.

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