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Effect of dynamic strain aging on the microstructure and mechanical properties of a reactor pressure vessel steel

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ABSTRACT

Analysis of the dynamic strain aging (DSA) effect was carried out for a reactor pressure vessel (RPV) steel, the A508-class3. The aging process includes the application of various plastic strain values of 1%, 2%, 4%, 6% and 8% with different strain rates at certain tempering temperatures. The microstructure of the specimens was analyzed in detail using optical microscopy, scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The results indicate that serrated stress–strain curves occurred at the DSA process, and the new hardening phase of $M_{23}C_6$ type carbide is precipitated to pin the mobile dislocations. The hardening effect increases with the increase of the strain value within the uniform plastic strain region, even though the softening effect caused by dynamic recovery is obvious. After analyzing the correlations between aging parameters, hardening, ductile-brittle transition temperature and irradiation effect, it is found that the degeneration of mechanical properties caused by DSA is similar to the irradiation effect.

1. Introduction

A508-class3 reactor pressure vessel (RPV) steel is commonly used in pressure boundary components of nuclear power plant and many studies have been reported in regard to structural failures because of radiation embrittlement [1–5]. Radiation embrittlement strongly degrades the mechanical properties of the RPV steels for the radiation-induced or radiation-enhanced formation of the precipitates, vacancies and dislocations during operation [6–10]. Since performing real irradiation tests is both complex and expensive, many degradation procedures have been devised to simulate the effect of neutron irradiation on the mechanical properties and microstructure of RPV steels.

Faulkner et al. [11–15] analyzed the difference between the radiation-induced grain boundary segregation and thermally induced non-equilibrium segregation, and presented wonderful similarity between the two segregation theories. In their work, it was concluded that the radiation-induced point defect and the diffusion and segregation of interstitial impurities can be calculated using thermally induced non-equilibrium segregation theory. Mathon et al. [16] and Pareige and Miller [17] indicated that the precipitation mechanism of the copper cluster in matrix after neutron irradiation is similar to the embrittlement thermal aging treatment at 500 °C. DiMelfi et al. [18] analyzed the difference of tensile true stress–strain curves between radiated nuclear steel and unradiated nuclear steel, and they found out that it is possible to simulate the macroscopic effects of matrix-defect (dislocations) hardening on the yield stress and work-hardening characteristics using the cold prestrain treatment. However, it could not simulate the phenomenon of interstitial impurities on the grain boundary. In order to combine the advantage of thermal aging treatment and cold prestrain treatment, Wu et al. [19–21] explored a thermo-mechanical embrittlement process (TMEP), which combines the tempering embrittlement and the prestraining hardening to simulate the neutron irradiation effects. The TMEP effects on the microstructure and properties of materials are dependent upon the combination of the TMEP parameters. It can be considered as static strain aging if the prestraining is applied after the thermal embrittlement, whereas it is defined as dynamic strain aging (DSA) when the deformation and thermal aging occur at the same time. Previous research [22] on the DSA in A508-class3 pressure vessel steel showed that serrated flow in stress–strain curves was observed at strain rates ($\sim 10^{-4}$) and temperature range 140–340 °C due to the solute atmospheres of nitrogen and carbon which can pin the mobile dislocation. However, the effect of embrittlement thermal aging on the precipitation and diffusion of interstitials is not enough at those lower temperatures and higher strain rates.

In the present work, a specially designed, modified DSA process by combining deformation and thermal aging was carried out. Microstructure and mechanical properties were characterized and analyzed. The effect of the process parameters on the microstructure and mechanical property was discussed.

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Table 1
Chemical composition of the material (wt%).

Element	C	Si	Mn	Cr	V	Cu	Ni	Mo	P	S
Content (wt%)	0.13	0.21	1.30	0.19	0.003	0.016	0.63	0.50	0.013	0.008

2. Experimental

The material used in this study was hot rolled 37 mm thick A508-class3 steel plate. The composition of the material is presented in Table 1.

The steel plate was subjected to the following heat treatment procedure which was regarded as the as-received condition: austenitizing at 880 °C for 1h and oil quench, tempering at 660 °C for 4h and then air cooling. The specimens were taken from the one-quarter thickness location from the surface.

Some of the as-received specimen blanks with the dimension of 38 mm gauge length and 15 mm diameter were subjected to DSA treatment which were regarded as the aged condition. The aging procedure parameters include aging temperature, strain rate and strain value. The strain rates were $1.1\times10^{-5}\,s^{-1}$ and $6.6\times10^{-5}\,s^{-1}$ and the tempering temperatures were 500 °C and 550 °C. Five different plastic strain values (1%, 2%, 4%, 6% and 8%) were applied to each temperature–strain rate combination condition to simulate the yield strength increases due to different dosage neutron irradiation [23].

DSA treatment was carried out using a hydraulic servo materials testing machine. The heating process was conducted using a chamber electronic furnace attached to the testing machine. After etching with a solution containing nitric acid of 5% in absolute ethyl alcohol, the microstructures of specimens were observed by a high resolution optical microscope. The dimension and distribution of the precipitates were measured using a field emission scanning electron microscope (SEM). Transmission electron microscope (TEM) samples were prepared by mechanical thinning to 50–100 μm, then by double-jet electrolytic thinning technique using a solution of 5% perchloric acid at −30 °C with the etching current of 25 mA, then observed using a high resolution TEM.

The tensile specimen with the dimension of 33 mm gauge length and 5 mm diameter and the V-notch Charpy impact specimens with the dimension of $10\times10\times55\,mm^3$ were used to determine the basic tensile and impact properties of the aged material. The test specimen geometry and the relative cutting position in the DSA treated specimen blanks are shown in Fig. 1.

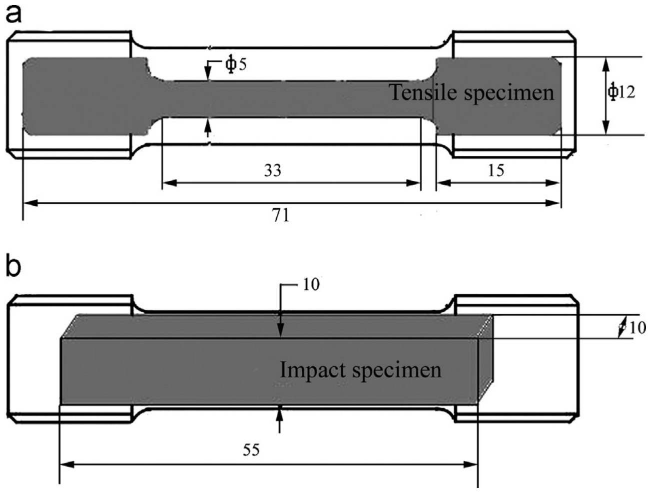

Fig. 1. (a) The aged tensile specimen. (b) The aged impact specimen. Shaded geometries are the test specimens cut from the DSA treated specimen blanks.

3. Results and discussion

3.1. DSA effect on the microstructure

The microstructure of the as-received material was granular bainite with obvious prior austenite grain boundaries, as shown in Fig. 2. The mechanical properties are provided in Table 2.

Fig. 3 shows the TEM images of aged specimens after DSA of $1.1\times10^{-5}\,s^{-1}$ at 500 °C. A small number of simple dislocation lines distribute in the matrix at low plastic strain (Fig. 3a). When plastic strain increases, some fine particles precipitated and pin the tangled dislocations (Fig. 3b).

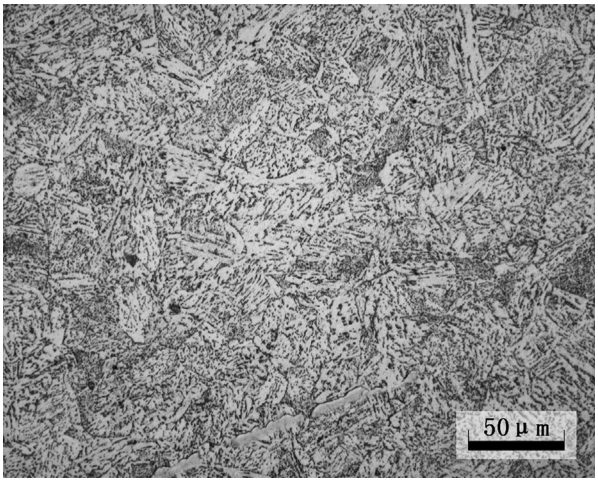

Fig. 2. Microstructure of the as-received A508-class3 steel.

Table 2
Mechanical properties of the as-received A508-class3 RPV steel.

Yield strength, σ_y (MPa)	Tensile strength, σ_b (MPa)	Specific elongation, δ (%)	Percentage reduction in area, ψ (%)	Impact toughness, *ak* (J/cm^2)	DBTT, vT_{r41} (°C)
490	595	24.4	66.3	179.5	−83

The precipitates of aged specimens after $6.6\times10^{-5}\,s^{-1}$/550 °C DSA were observed by SEM, as shown in Fig. 4. The microstructure in Fig. 4a, corresponding to the 2% plastic strain, demonstrates that few precipitates precipitated within the grains and at the prior austenite grain boundaries. Many precipitated phases can be seen scattered within the austenite grain at the 4% plastic strain (Fig. 4b). With the plastic strain increasing, it can be seen that the number of precipitates increases which are dispersed in the prior austenite grains, grain boundaries and bainite plate interfaces (Fig. 4c and d). Fig. 5 shows the image of the precipitates within the grain in large magnification, it indicated that more and more precipitates distributed in the bainite plate with the increasing of plastic strain value. The shapes of precipitates are small short rod and spherical and the size of the precipitates is measured to be about 100–300 nm.