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The effects of strain rate and carbon concentration on the dynamic strain aging of cold rolled Ni-based alloy in high temperature water

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ABSTRACT

The effect of strain rate on dynamic strain aging of cold-rolled Ni-based alloy was investigated. With decreasing strain rate, the stress amplitude of serrations first increased and then saturated. Compared with the solution-annealed condition, the thermally-treated condition produced smaller stress amplitudes that saturated at a lower strain rate. Observations are consistent with a mechanism in which the locking strength of solute atmospheres first increases with increasing solute atom arrival at dislocations and gradually saturates as solute reaches a critical level.

Serrated plastic flow (dynamic strain aging (DSA) or Portevin–Le Chatelier (PLC)) is observed in many alloys during deformation in specific temperature and strain rate ranges. It is widely believed that it arises from the interactions between diffusing solute atoms and mobile dislocations that are temporarily impeded [1,2]. Much previous work has been done to investigate the influence of different variables on DSA. Related work [3–12] on different alloys show that increasing strain rate results in decreasing amplitude of the stress drop. The lowest strain rate applied in those works was 10^{-7} s^{-1}. Because many important phenomena, such as stress corrosion cracking, occur at strain rates below this level, it is of interest to understand DSA behavior at lower strain rates. The alloy of interest in this work is Alloy 690 which is widely used in nuclear power plant components exposed to high temperatures and low strains. The typical creep rate of this alloy in simulated pressurized water reactor primary water environment is in the range of 10^{-10}–10^{-9} s^{-1} [13]. The effect of carbon concentration was also studied by testing samples subjected to different thermal treatments. To date, very limited work has been done to study the DSA of this alloy [9,14,15].

The chemical composition of Alloy 690 used in this work is 57.6 wt.% Ni, 32.7% Cr, 8.64% Fe, 0.25% Mn, 0.315% Al, 0.08% Si and 0.02% C. The alloy was received as a forged bar with a diameter of 185 mm. It was solution annealed (SA) at 1100 °C for 1 h and then water quenched. In order to change the carbon concentration in matrix, some solution annealed samples were thermally treated (SA + TT) at 700 °C for 17 h and cooled in air. Both SA and SA + TT samples were then cold rolled (CR) to 20% thickness reduction, resulting in a sheet of approximately 8 mm in thickness. The cold rolled sheet was machined into round tensile bars with the sample axis in the rolling direction. The gage section of the tensile bar is 20 mm in length and 2 mm in diameter. Samples were mechanically abraded up to 4000 grit and then electropolished for 30 s at 30 V in a solution of 10% (volume fraction) perchloric acid in methanol. Some coupons were also prepared for carbide analysis using the same procedure. Grain boundary carbides were characterized with scanning electron microscope (SEM) on a FEI Helios Nanolab 650. Tensile bars were strained to failure in 360 °C high purity water containing 1.62 ppm hydrogen (by weight) which is approximately at the electrochemical potential of the Ni/NiO phase boundary. The inlet resistivity was above 18 MΩ cm and the outlet resistivity was above 5 MΩ cm. A recirculating water loop equipped with a 4 L stainless steel autoclave was used to maintain the required water environment. Samples were strained with a 5 K servo via a crosshead that was capable of loading a maximum of 4 tensile bars.

Fig. 1 shows the SEM images of these two samples. The SACR sample shows no significant grain boundary carbide precipitation while SA + TTCR sample has dense semi-continuous carbides. The remaining C concentration in SA + TTCR sample was estimated using the computer code DEPLETE690 [16]. The code contains a thermodynamic and kinetic analysis of grain boundary carbide precipitation in alloy 690 as a function of alloy content and time

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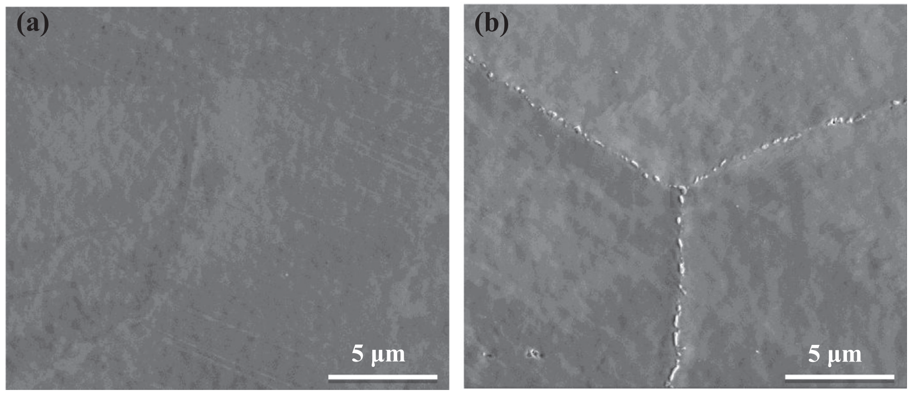

Fig. 1. SEM images of (a) SACR and (b) SA + TTCR samples.

at temperature and has been benchmarked against experimental measurement [16]. From the calculation, the C concentration in the matrix decreased from 0.94 at.% to 0.78 at.% after the thermal treatment at 700 °C for 17 h.

After the desired water environment stabilized, the samples were first loaded to just below the yield point at a rate of $1.24 \times 10^{-5}\,s^{-1}$ and then strained to failure at various extension rates. Four nominal strain rates were used: $2.5 \times 10^{-7}\,s^{-1}$, $5 \times 10^{-8}\,s^{-1}$, $2.5 \times 10^{-8}\,s^{-1}$ and $1 \times 10^{-8}\,s^{-1}$. The samples were designated by the thermal mechanical treatment and applied strain rate. For example, the solution annealed and cold rolled sample strained at $2.5 \times 10^{-7}\,s^{-1}$, $5 \times 10^{-8}\,s^{-1}$, $2.5 \times 10^{-8}\,s^{-1}$ and $1 \times 10^{-8}\,s^{-1}$ was designated as SACR-0, SACR-1, SACR-2 and SACR-3, respectively.

Fig. 2a and b shows the stress–strain curves for SACR and SA + TTCR samples at the four different strain rates. For better view, the curves on each graph were separated and the two upper curves share the right *y* axis. All the y axes have the same scale spacing. The rising part of the serrations is elastic and the apparent modulus is unchanged with strain rate. Serrations occurred shortly after yielding, and by their shape, fall into the definition of type C which is due to dislocation unlocking [1]. R. W. Hayes and W. C. Hayes [7] reported that the activation energy of DSA for a nickel-based alloy (Waspalloy) in the temperature range of 204–649 °C is consistent with a carbon atmosphere aging mechanism. The work of Hänninen et al. [14] also suggests that the serrated plastic flows of alloy 600 and 690 at temperature of 100–600 °C result from carbon-dislocation interaction. So it is believed that the serrations in alloy 690 at 360 °C are due to carbon atmospheres formed at dislocations.

Serrations occurred in different plastic strain ranges for different samples. To compare different samples, only the serrations

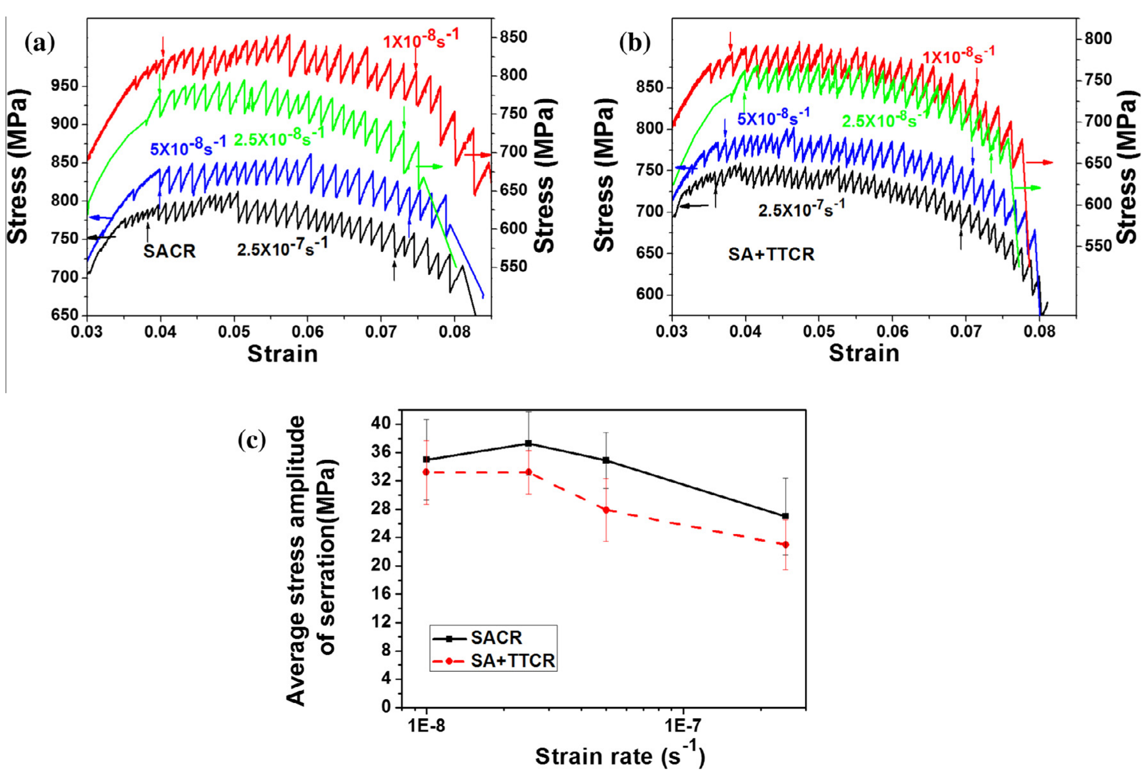

Fig. 2. Serrations in stress–strain curves of (a) solution annealed and cold rolled and (b) solution annealed + thermally treated and cold rolled Alloy 690 strained at different rates in 360 °C water (the vertical arrows indicate the starting and ending serrations used for the calculation of average stress amplitudes, and the horizontal arrows indicate the stress scale for the plot); (c) the changes of average stress amplitudes of serration (in the plastic strain range of 0.4–4%) with strain rate.