High temperature properties of an austenitic stainless steel

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Abstract. Tensile properties of the 18Cr-9Ni-W-Nb-V-N austenitic stainless steel were studied at strain rates ranging from 6.7×10^{-6} to 1.3×10^{-2} s^{-1} in the temperature interval 20–740°C. It was found that this steel exhibits jerky flow at temperatures ranging from 530 to 680°C and an initial strain rate of 1.3×10^{-3} s^{-1}. This phenomenon was interpreted in terms of Portevin-Le Chatelier (PLC) effect occurring due to dynamic strain aging (DSA). PLC yields significant increase in high temperature strength of this steel due to extending of plateau on temperature dependence of yield strength (YS) and ultimate tensile strength (UTS) to higher temperatures. As a result, YS and UTS remain virtually unchanged with increasing temperature from 350 to 740°C. Role of additives of tungsten and vanadium in DSA and high temperatures strength of the austenitic stainless steel is discussed.

1. Introduction

Austenitic stainless steels, containing 18% of Cr and 8% of Ni, are widely used in high temperature applications. Additives of W, V, Nb and N provide an increment in their service temperature [1]. However, the origin of positive effect of these elements on high temperature strength is not yet clear. It has been reported that at high service temperatures the austenitic stainless steels are susceptible to dynamic strain aging (DSA) associated with interactions between solute atoms and mobile dislocations during plastic deformation. This phenomenon depends on temperature and strain rate. DSA may have a large impact on the mechanical properties such as strength, ductility, fatigue and creep life of high temperatures structural units [2-4]. The present study aimed to examination of DSA phenomenon in the 18Cr-9Ni-W-Nb-V-N steel and its effect on strength at high temperature. A role of alloying elements in high temperature strength of the 18Cr-9Ni-W-Nb-V-N austenitic steel is discussed.

2. Experimental procedures

The austenitic stainless steel with a chemical composition Fe–0.018%C–18.2%Cr–8.2%Ni–2.1%W–0.43%Nb–0.29%V–0.17%N–1.75%Mn–0.14%Si was manufactured by chill casting. The ingots were forged into rods at a temperature of ~1180°C, then solution treated at 1150°C for one hour and quenched into water. The flat tensile specimens having a gauge length of 25 mm and 7×3 mm^2 cross-section were cut from solution treated rods. These specimens were tensioned in the temperature interval of 20–740°C at strain rates ranging from 6.7×10^{-6} to 1.3×10^{-2} s^{-1}. An Instron universal testing machine (Model 5882) equipped with a three-zone split furnace was used. Temperature accuracy was within ±3°C. Each specimen was held at a testing temperature for about 20 minutes in order to reach a thermal equilibrium.

Specimens for metallographic examinations were etching in a solution of 30%H_2O+30% HCl+10%HNO_3. Metallographic analysis was carried out using Olympus GX70. For TEM examinations, samples were ground to about 0.1 mm. Discs with 3 mm diameter were cut and electropolished to perforation with a Tenupol-5 twinjet polishing unit using a 10%$HClO_4$ in CH_3COOH at 25 V. A Jeol JEM-2100 electron microscope with a double-tilt stage at an accelerating voltage of 200 kV was used for the thin foil examinations.

3. Results and discussion

Typical microstructure of solution treated steel consists of fully annealed austenitic grains containing annealed twins and small amount of fine second phase particles (figure 1). Dispersoids having average size of about 50 nm and located within austenitic grains was identified as a primary NbCrN. The average size of austenitic grains was about 16 μm. Energy-dispersive X-ray spectroscopy showed that alloying elements fully dissolves in matrix (figure 2).

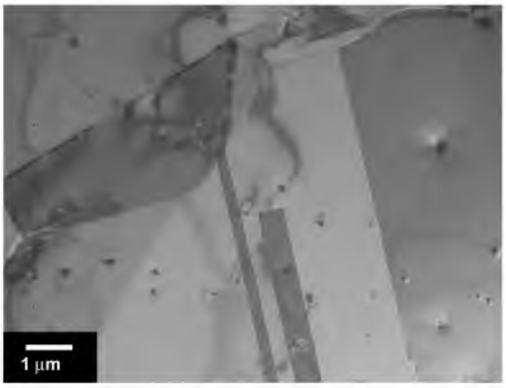

Figure 1. TEM micrograph showing typical microstructure of 18Cr-9Ni-W-Nb-V-N steel.

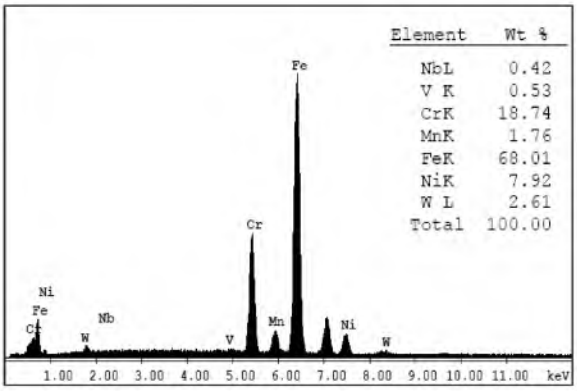

Figure 2. EDS spectra and quantification of elements taken from precipitations free matrix.

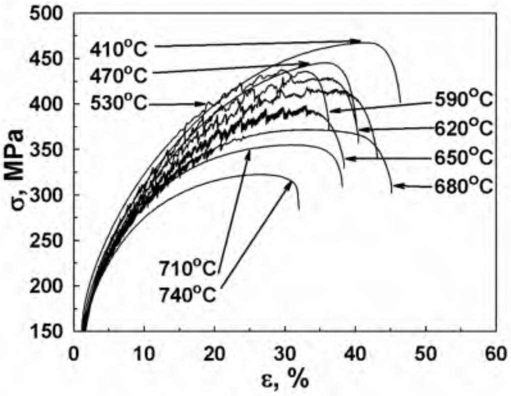

Figure 3. Typical stress–strain curves obtained at strain rate of 1.3×10^{-3} s^{-1}.

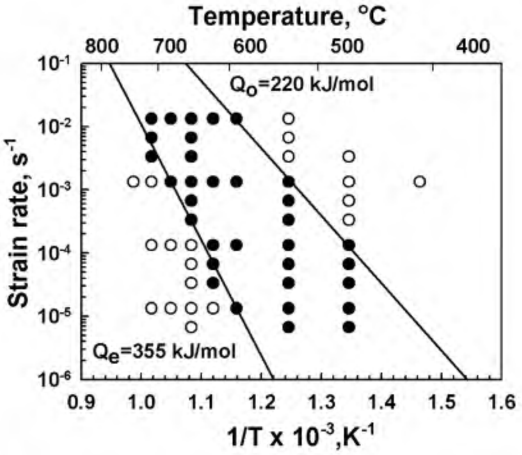

Figure 4. Test conditions where serrations occurred during tensile tests (open symbols: no serration, closed symbols: serration).

It was found that deformation behavior of the 18Cr-9Ni-W-Nb-V-N steel characterized by discontinuous plastic flow manifested as serrations on the stress–strain curves. The typical stress–strain curves obtained in the temperature interval from 410 to 740°C at a strain rate of ~ 1.3×10^{-3} s^{-1} are shown in figure 3. Different types of jerky flow observed on stress–strain curves in the temperature interval 530–680°C (figure 3) suggest the occurrence of various mechanisms of DSA. This assumption is supported by difference in activation energy for the onset and the end of jerky flow calculated as the slope of the boundaries delineating serrated flow regime in an $\ln\dot{\varepsilon}-1/T$ plot (figure 4). Values of activation energy were of 220 kJ/mol and 355 kJ/mol for the onset (Q_o) and the end (Q_e) of jerky flow, respectively. Several studies were dedicated to mechanism and activation energy for dynamic strain aging in austenitic stainless steel [3-6]. As a rule, diffusion of interstitial solutes and substitutional solutes to dislocations is considered to be the mechanisms responsible for jerky flow at low and high temperatures, respectively. However, the values of activation energy calculated for 18Cr-9Ni-W-Nb-V-N steel are considerably higher than that reported previously for the 18Cr-9Ni type austenitic steels at the same strain rate – temperature conditions. For example, in type 304 austenitic steels the activation energy for the onset and the end of jerky flow was found to be ~200 kJ/mol and ~290 kJ/mol, respectively [5]. The examined steel contains W, V, Nb and N in solid solution (figure 2). It is widely known [4] that nitrogen has a strong effect on the value of activation energy due to high interaction energy with chromium. However, Kim et el. [4] reported the value of activation energy for the onset and the end of serrations of 109 and 320 kJ/mol in 316 austenitic steel with nitrogen content of ~0.15%. Notably, that nitrogen content in the present steel is almost the same. It seems, that W, Nb and V dissolved in solid solution increase the values of activation energy due to strong interaction between mobile dislocations and solute atoms in the 18Cr-9Ni-W-Nb-V-N steel. This interaction impedes dislocation mobility affecting strength of this steel. However, additional examination of microstructure evolution during high temperature tensile test is necessary to define the actual role of these alloying elements. To confirm the influence of DSA on the strength the tensile properties of presented steel were examined at strain rate of 1.3×10^{-3} s^{-1} in the temperature interval 20–740°C.

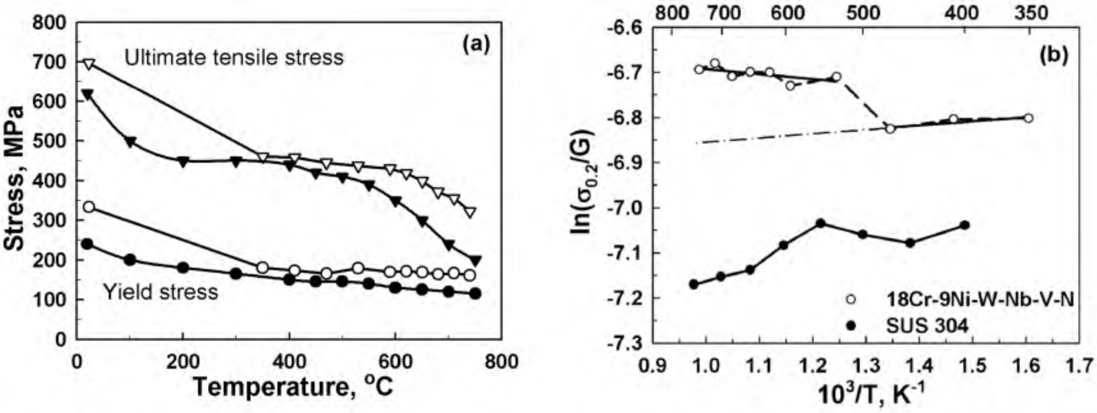

Figure 5. The variation of tensile properties with temperature at an initial strain rate 1.3×10^{-3} s^{-1} (a). Yield stresses normalized by the shear modulus *vs.* reciprocal temperature (b) (open symbols: 18Cr-9Ni-W-Nb-V-N steel, closed symbols: SUS304 steel [7]).

Yield stress (YS) and ultimate tensile stress (UTS) were plotted as a function of temperature in figure°5a. The temperature dependence of YS and UTS for SUS304 austenitic steel [7] is also presented for comparison. It is clearly seen that the 18Cr-9Ni-W-Nb-V-N steel demonstrates increased value of YS and UTS at all temperatures. The values of YS of SUS304 steel decrease with increasing temperature while these values for the 18Cr-9Ni-W-Nb-V-N steel remain virtually unchanged at temperatures > 350°C. The plateau of YS at the stress level of about 168 MPa was found (figure 5a).

In order to examine temperature dependence of yield stress for the 18Cr-9Ni-W-Nb-V-N steel in details the shear modulus compensated yield stress was plotted against the reciprocal absolute temperature in logarithmic scale (figure°5b). For the SUS304 the values of yield stress normalized on temperature dependence of shear modulus steel decrease with increasing temperature excepting short temperature interval where DSA effect was found. On the other hand, for the 18Cr-9Ni-W-Nb-V-N steel the normalized YS increases with increasing temperature from 530 to 740°C. Thus, positive temperature dependence of $\sigma_{0.2}/G$ takes place providing high strength of the steel examined in a wide temperature interval. It is obvious that this positive temperature dependence is attributed to the PLC effect.

In the temperature interval 350–680°C where DSA occurred, the values of UTS of the 18Cr-9Ni-W-Nb-V-N steel remain almost unchanged; plateau is observed at these temperatures (figure 5a). At high temperatures, UTS decreases extensively. It is seen in figure 5a, that at $T > 530°C$ the present steel demonstrates values of UTS significantly higher than that for the SUS304 steel. It is known that the strong interaction between mobile dislocations and solute elements provides accumulation of lattice dislocations in DSA regime [8,9]. As a result the values of UTS increase at temperatures there DSA occurs. Therefore, it is possible to conclude that additional additives of W, Nb and V to 18%Cr-8%Ni steel lead to extension of the DSA regime to higher temperatures providing high value of UTS. As a result, the 18Cr-9Ni-W-Nb-V-N steel exhibits increased high temperature strength.

4. Conclusions

1. PLC effect was found in the 18Cr-9Ni-W-Nb-V-N steel with following typical attributes: jerky flow; the plateaus on temperature dependencies of YS and UTS; positive temperature dependence of $\sigma_{0.2}/G$.
2. The extending of DSA to higher temperature due to additions of W, Nb and V increases high temperature strength of the 18Cr-9Ni-W-Nb-V-N steel and provides high value of YS and UTS up to 740°C and 680°C, respectively.

Acknowledgements

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