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EFFECTS OF PRE-STRAIN AND TEMPERATURE ON IMPACT DEFORMATION BEHAVIOUR OF 304L STAINLESS STEEL

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ABSTRACT

This paper employs a compressive split-Hopkinson pressure bar to investigate the impact deformation and fracture behaviour of 304L stainless steel. Annealed 304L stainless steel bars are pre-strained to strains of 0.15 or 0.5 and are machined into cylindrical compression specimens. Impact tests are then performed at strain rates ranging from 2000 to 6000 s-1 at temperatures of 300℃, 500℃ and 800℃. The experimental results show that the flow stress increases with increasing pre-strain and strain rate, but decreases with increasing temperature. Negative and near-zero work hardening rates are found in the specimens pre-strained to 0.5 and then deformed at 300℃ and 500℃, respectively. The strain rate sensitivity of the pre-strained specimens increases with increasing strain rate, but decreases with increasing temperature. The highest strain rate sensitivity is found in the specimen pre-strained to 0.5 and then tested at a temperature of 300℃ under a strain rate of 6000 s-1. OM and SEM observations of the fracture surfaces show that the formation of adiabatic shear bands is the dominant fracture mechanism in 304L stainless steel specimens pre-strained to 0.5 and then deformed at temperatures of 300℃ or 500℃.

INTRODUCTION

304L stainless steel is widely used throughout the chemical, machinery, automobile and nuclear industries, and thus its mechanical properties and fracture mechanisms are of significant interest. The quasi-static mechanical behaviour of 304L stainless steel has been widely reported by many investigators [1-3]. The basic mechanical properties of 304L stainless steel obtained from these studies and others are readily available in material handbooks [4-5].

Products fabricated from 304L stainless steel are commonly subjected to impact loads during their service lives. As a result, a detailed knowledge of the impact response of 304L stainless steel is required in order to ensure the mechanical integrity of such components during their daily use. Stout et al. [6] and Harvey II et al. [7] studied the impact behaviour of 304L stainless steel by performing split-Hopkinson pressure bar experiments and Charpy tests, respectively. However, the impact performance of 304L stainless steel is affected not only by the loading rate, but also by the test temperature and the specimen deformation prior to testing. Staudhammer and Murr [8] investigated the effect of prestrain on the microstructural evolution of 304L stainless steel under explosive forming ($\dot{\varepsilon} > 10^6$ s^{-1}) and showed that many differences exist in the effects of static and dynamic loading on the mechanical properties and microstructure of prestrained materials. For example, adiabatic shear bands are not formed under static loading conditions, but are commonly observed in high-speed machining or forming specimens, forged components, or in vehicular components following a crash. The mechanisms responsible for the formation of adiabatic shear bands appear to be material dependent. As a result, it is necessary to establish the exact relationship between the formation of adiabatic shear bands and the strain rate, prestrain and temperature, respectively, on a case-by-case basis.

In previous studies [9-12], the current group examined the effects of prestrain on the impact mechanical behaviour of 304L stainless steel under room temperature conditions. By contrast, the objective of the present study is to investigate the effects of prestrain on the impact response of 304L stainless steel under high temperature conditions. Accordingly, a compressive split-Hopkinson pressure bar (SHPB) is used to examine the deformation response of annealed 304L stainless steel specimens prestrained to strains of 0.15 or 0.5 and then impacted at strain rates ranging from 2000 to 6000 s^{-1} at temperatures of 300℃, 500℃ and 800℃.

EXPERIMENTAL PROCEDURE

304L stainless steel bars with a composition of 17.91% Cr, 9.21% Ni, 1.47% Mn, 0.41% Si, 0.23% Mo, 0.09% V, 0.021% P, 0.024% S, 0.034% C and a balance of Fe were purchased from Eastern Steel Corp., USA. Upon receipt, the bars were annealed for 0.5 h at 1050℃ and were then quenched in water to obtain a zero prestrain condition. 20 mm thick sections were then cut from the annealed rods and deformed to prestrains of either 0.15 or 0.5 using a Saginomiya 100 (Japan) metal forming machine. Cylindrical specimens with a length and diameter of 9.7 mm were then prepared from the pre-deformed specimens.

Impact tests were carried out at temperatures of 300℃, 500 ℃ and 800℃ under strain rates ranging from 2000 to 6000 s^{-1}. A full description of the SHPB system and test procedure are provided in [13]. To obtain the elevated test temperatures considered in the present study, the specimens were enclosed in a clamshell radiant-heating furnace with an internal diameter of 25 mm and a heating element of length 300 mm. The specimen temperature was regulated by a Eurotherm 211 programmer / controller connected to an Inconel sheathed chromel-alumel thermocouple with a 1.5 mm diameter attached to the specimen. Prior to each test, the specimen and the two ends of the pressure bars holding the specimen were maintained at the specified test temperature for approximately 10 min to ensure a uniform temperature distribution at the specimen / pressure bar interface. The resulting temperature gradients induced along the lengths of the two pressure bars affect both the elastic modulus of the bars and the propagation velocity of the incident, reflected and transmitted pressure pulses. Accordingly, the original equations used to compute the strain, strain rate and stress in the deformed specimens [13] were modified to the form shown by Chiddister and Malvern in [14] and the current authors in [15].

The impacted specimens were mounted in epoxy resin, ground progressively using a series of abrasive papers with grit sizes ranging from 180 to 1200-mesh, polished with a micro-cloth dipped in a slurry of 0.3 μm alumina, and then etched in a solution of 1 part HNO_3, 1 part HCl and 1 part H_2O for approximately 3 minutes. The microstructures of the impacted specimens were observed using optical microscopy (OM) in order to examine the nucleation and growth of the adiabatic shear bands.

RESULTS AND DISCUSSIONS

3.1 Stress-strain curves

Figures 1 and 2 show the stress-strain curves of the 0.15 and 0.5 prestrained specimens, respectively, when deformed at strain rates ranging from 2000 to 6000 s^{-1} and temperatures of 300℃, 500℃ and 800℃. In general, it can be seen that the mechanical behaviour of the 304L stainless steel specimens is significantly dependent on the prestrain, strain rate and temperature. For a given prestrain, the flow stress increases with increasing strain rate, but decreases with increasing temperature. As the strain rate increases, the rate of multiplication of the dislocations also increases, and the dislocations become increasingly entangled. These tangled structures suppress the slip of the dislocations within the microstructure, and therefore increase the flow stress. Conversely, the flow stress reduces with increasing temperature since a higher temperature increases the thermal energy provided to the dislocations and therefore improves their ability to overcome the short-range obstacles to motion posed by the tangled dislocation structures.

Comparing Figs. 1 and 2, it is observed that for a given temperature, the flow stress generally increases with increasing prestrain. For example, given a temperature and strain rate of 300℃ and 6000 s^{-1}, respectively, the flow stress increases by around 400 MPa as the prestrain is increased from 0.15 to 0.5. However, the effect of the prestrain on the flow stress reduces with an increasing temperature. For example, at a temperature of 500℃, the increase in the flow stress reduces from 400 MPa to 370 MPa, while for the highest temperature of 800℃, the flow stress curve of the specimen prestrained to 0.5 is almost identical to that of the specimen prestrained to 0.15. In other words, the prestrain has virtually no strengthening effect at very high temperatures. This finding is reasonable since under high temperature conditions, the microstructure transforms to a full FCC austenite structure irrespective of the amount of prestrain applied to the original (i.e. undeformed) specimen.

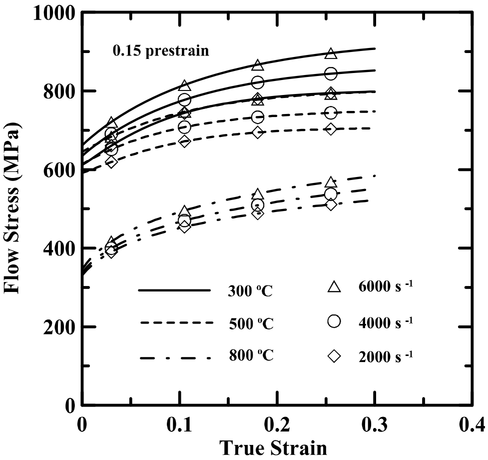

Figure 1 Stress-strain curves of 0.15 prestrained specimens under different strain rates and temperatures.

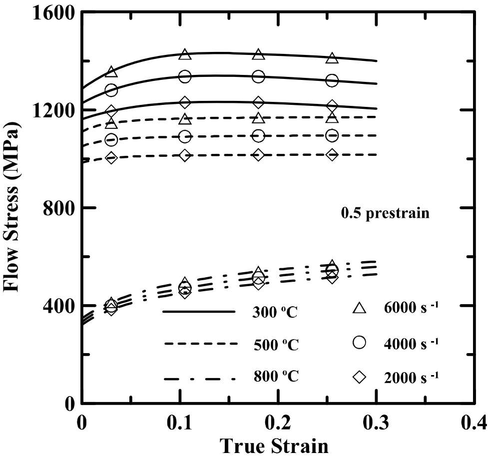

Figure 2 Stress-strain curves of 0.5 prestrained specimens under different strain rates and temperatures.

3.2 Work hardening behaviour

Figure 1, corresponding to a prestrain of 0.15, shows that the flow stress increases more slowly with increasing strain at a temperature of 500℃ than at a temperature of 300℃ or 800℃. Meanwhile, in Fig. 2, corresponding to a prestrain of 0.5, the flow stress increases more rapidly with increasing strain at 800

℃ than at either 300℃ or 500℃. The effects of the prestrain, strain rate and deformation temperature on the plastic deformation of the present 304L stainless steel specimens can be analysed using the work hardening rate parameter, defined as $\partial\sigma/\partial\varepsilon$. Figures 3 and 4 present the variation of the work hardening rate with the true strain for prestrains of 0.15 and 0.5, respectively. In both cases, the work hardening rate reduces with increasing strain. However, it is evident that the work hardening rate is significantly dependent on the temperature, strain rate and prestrain. For example, Fig. 3 shows that for the 0.15 prestrained specimens, the work hardening rate increases with increasing strain rate given a constant deformation temperature. Furthermore, for a given strain rate, the work hardening rate reduces as the temperature is increased from 300 ℃ to 500℃, but increases as the temperature is further increased to 800℃. In Fig. 4, corresponding to a prestrain of 0.5, the work hardening rate increases with increasing strain rate at true strains of less than 0.15 and deformation temperatures of 300℃ and 500℃, but increases with increasing strain rate at all values of the true strain at a higher deformation temperature of 800℃. Interestingly, a negative work hardening tendency is observed in the 0.5 prestrained specimen at a strain of 0.15 and a temperature of 300℃. That is, the work hardening rate at a strain rate of 6000 s^{-1} is lower than that at a strain rate of 2000 s^{-1}. Comparing the results presented in Figs. 3 and 4, it is observed that the work hardening rate in the specimens prestrained to 0.5 is lower than that in the specimens prestrained to 0.15 at temperatures of 300℃ or 500 ℃, but is almost identical to that of the specimen prestrained to 0.15 at a temperature of 800℃.

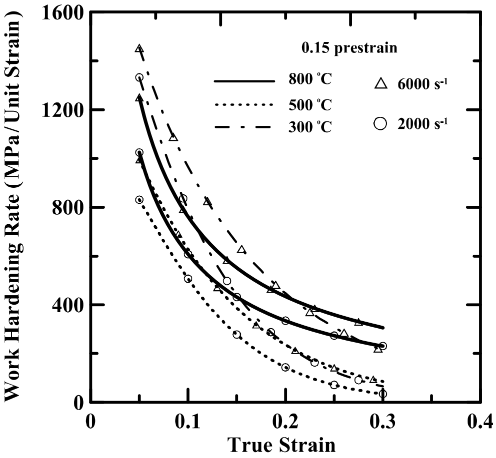

Figure 3 Work-hardening rate of 0.15 prestrained specimens under different temperatures and strain rates.

In Fig. 4, the negative and near-zero work hardening rates observed in the 0.5 prestrained specimens at temperatures of 300℃ and 500℃, respectively, indicate that the thermal softening effect is more significant than the work hardening effect and causes the formation of an adiabatic shear band due to the resulting flow instability. The temperature rise causes a thermal softening effect, and therefore affects the stress-strain response of the deformed material. Since it is difficult to obtain precise measurements of the temperature rise (ΔT) during high speed loading, ΔT is generally calculated theoretically in accordance with $\Delta T = 1/(\rho C_p)\int_0^{\varepsilon}\sigma d\varepsilon$, where ρ is the density (i.e. 7.9 g/cm^3 for 304L stainless steel), Cp is the heat capacity (477 J/(kg·K), σ is the stress, and dε is the strain interval. Figure 5 shows the relationship between the temperature rise and the true strain for prestrains of 0.15 and 0.5 and strain rates of 2000 s^{-1} and 6000 s^{-1}. From inspection, the maximum temperature (~110K), i.e. the greatest softening effect, occurs in the specimen prestrained to 0.5 and then tested to a true strain of 0.3 at a strain rate of 6000 s^{-1}.

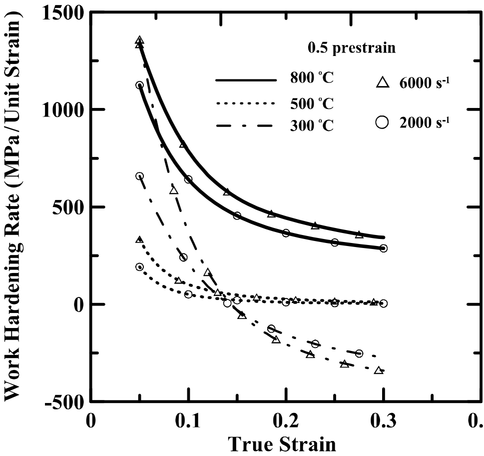

Figure 4 Work-hardening rate of 0.5 prestrained specimens under different temperatures and strain rates.

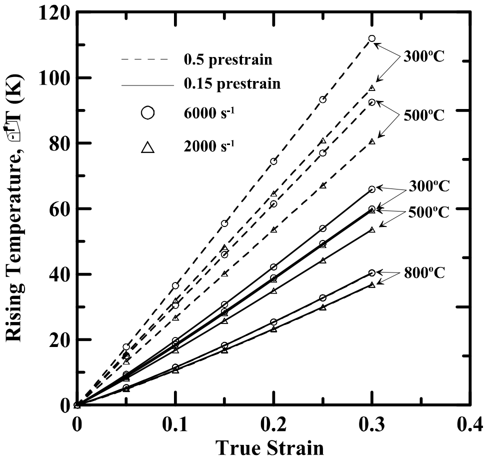

Figure 5 Variation of deformation-induced temperature rise as function of strain and strain rate.

3.3 Strain-rate sensitivity

The dependence of the strain rate effect on the prestrain, strain rate and temperature can be quantified via the following strain rate sensitivity parameter:

$$\beta = (\sigma_2 - \sigma_1)/\ln(\dot{\varepsilon}_2/\dot{\varepsilon}_1), \qquad (1)$$

where the compressive stresses σ_2 and σ_1 are obtained from tests conducted at average strain rates of $\dot{\varepsilon}_2$ and $\dot{\varepsilon}_1$, respectively. Figures 6(a) and 6(b) present the variation of the strain rate sensitivity with the true strain as a function of the strain rate and temperature for the 0.15 and 0.5 prestrained specimens, respectively. In both cases, it can be seen that the strain rate sensitivity increases with increasing strain rate, but decreases with increasing temperature. In addition, it is observed that the strain rate sensitivity increases in the higher strain rate range (i.e. 4000~6000 s^{-1}). In the 0.15 prestrained specimens, the strain rate sensitivity increases with increasing strain (see Fig. 6(a)). However, in the 0.5 prestrained specimens, the strain rate sensitivity remains approximately constant for all values of the applied strain. Comparing Figs. 6(a) and 6(b), it can be seen that the strain rate sensitivity of the 0.5 prestrained specimens is notably higher than that of the 0.15 prestrained specimens at temperatures of 300 ℃ or 500 ℃, but is approximately equal to that of the 0.15 prestrained specimens at a higher temperature of 800℃.

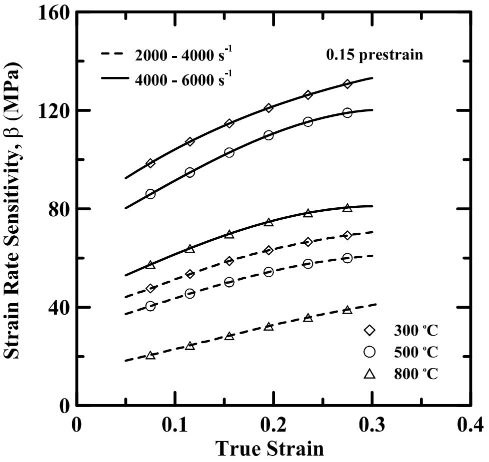

Figure 6(a) Strain rate sensitivities of 0.15 prestrained specimens as function of true strain, strain rate and temperature.

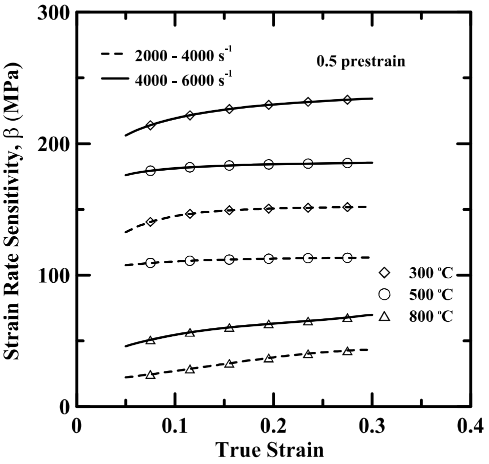

Figure 6(b) Strain rate sensitivities of 0.5 prestrained specimens as function of true strain, strain rate and temperature.

3.4 Fracture observations

It is well known that specimens deformed under high speed loading and low temperature conditions form adiabatic shear bands [16]. Adiabatic shear bands were also observed in some of the prestrained 304L stainless steel specimens deformed in the present study under high temperature conditions. It is found that adiabatic shear bands are formed in the specimens prestrained to 0.5 and then impacted at temperatures of 300℃ or 500℃. Figures 7(a) and 7(b) present OM photographs of the adiabatic shear bands formed in the 0.5 prestrained specimens deformed at 300℃ under strain rates of 2000 s^{-1} and 6000 s^{-1}, respectively. The photographs show that the specimens contain only one shear band propagating diagonally toward the centre of the specimen at an angle of 45° to the loading direction and containing no branches. The resulting flow localisation effect is evident in both the stress-strain curves in Fig. 2 and the work hardening rate curves in Fig. 4, in which it can be seen that the work hardening rate of the corresponding specimens is negative or near zero. Of the specimens prestrained to 0.5 and then impacted at temperatures of 300℃ or 500℃, cracks are formed in the adiabatic shear bands of the specimens impacted at a temperature of 300℃ and a strain rate of 4000 s^{-1} or 6000 s^{-1}. These cracks represent a significant zone of weakness within the deformed specimen. Although the adiabatic shear bands have a narrow width (e.g. ~ 50 μm), they prompt the initiation of voids and cracks, and thus as shown in Fig. 5, a negative or near-zero work-hardening rate is observed in the 0.5 prestrained specimens impacted at temperatures of 300℃ and 500℃, respectively.

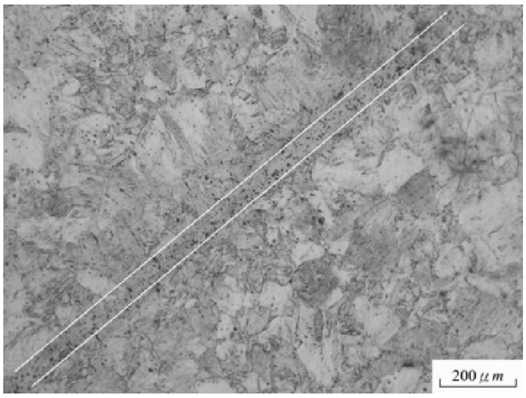

Figure 7(a) OM photographs of adiabatic shear bands in 0.5 prestrained specimens tested at 2000 s^{-1}, 300℃.

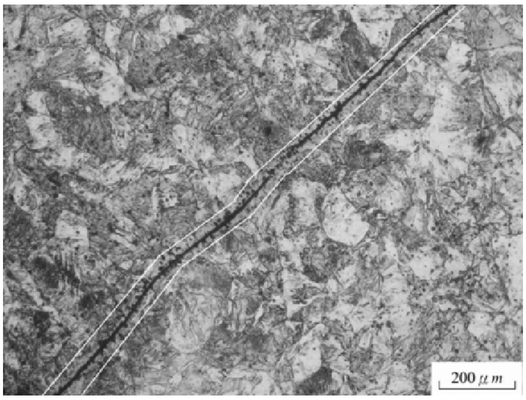

Figure 7(b) OM photographs of adiabatic shear bands in 0.5 prestrained specimens tested at 6000 s^{-1}, 300℃.

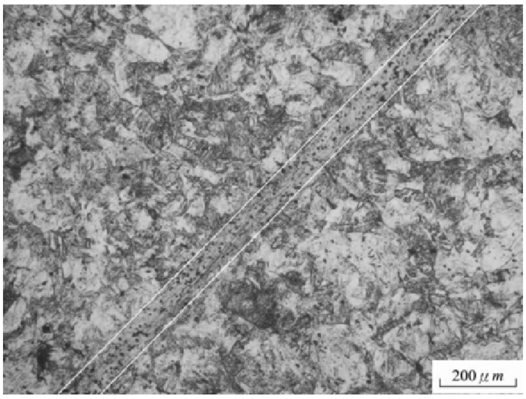

Figure 7(d) OM photographs of adiabatic shear bands in 0.5 prestrained specimens tested at 6000 s^{-1}, 500℃.

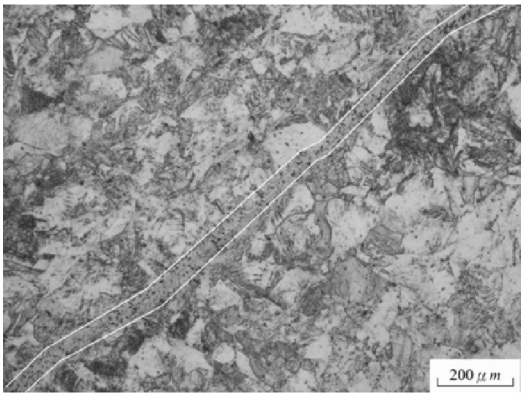

Figure 7(c) OM photographs of adiabatic shear bands in 0.5 prestrained specimens tested at 2000 s^{-1}, 500℃

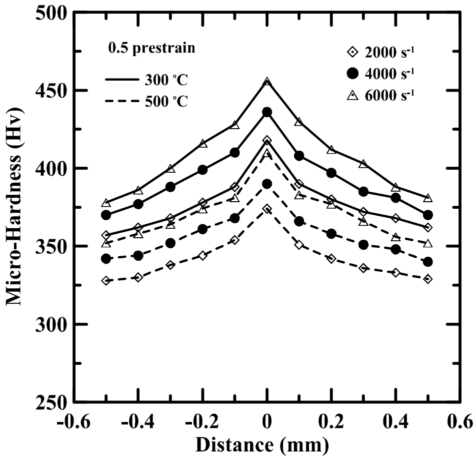

Figure 8 Microhardness of adiabatic shear bands in 0.5 prestrained specimens under different strain rates and temperatures.

Figures 7(c) and 7(d) show that the adiabatic shear bands formed in the 0.5 prestrained specimens deformed at a temperature of 500℃ have no cracks. However, the adiabatic shear bands still represent a weak point within the deformed microstructure since the rapid phase transformation of the deformed area causes the adiabatic shear band to be brittle and hard compared to the surrounding matrix. Figure 8 shows the variation of the microhardness across the width of the adiabatic shear bands in the 0.5 prestrained specimens deformed at temperatures of 300℃ and 500℃, respectively. It is seen that for each temperature and strain rate condition, the hardness has a maximum value in the centre of the shear band and reduces smoothly toward that of the matrix on either side. It is also observed that the hardness of the adiabatic shear band increases with increasing strain rate, but reduces with increasing temperature. This tendency suggests that the effect of adiabatic heating on the shear band hardness is dominated by both the strain rate and the temperature.

CONCLUSION

This study has investigated the mechanical response of prestrained 304L stainless steel at strain rates ranging from 2000 to 6000 s^{-1} and temperatures of 300℃, 500℃ and 800℃, respectively. The results have shown that the deformation behaviour of prestrained 304L stainless steel is highly sensitive to the prestrain, strain rate and temperature. The flow stress increases with increasing prestrain and strain rate, but decreases with increasing temperature. The work hardening rate in the specimens prestrained to 0.5 is lower than that in the specimens prestrained to 0.15 at temperatures of 300℃ or 500℃, but is similar to that in the specimens prestrained to 0.15 at the highest test temperature of 800℃. In addition, a negative work hardening rate is observed in the specimens prestrained to 0.5 and then deformed at a temperature of 300℃. The strain rate sensitivity of the 304L stainless steel specimens increases with increasing prestrain and strain rate, but decreases with increasing temperature. The temperature sensitivity increases with increasing prestrain, strain rate or temperature. The microstructural observations show that the specimens prestrained to 0.5 and then deformed at temperatures of 300℃ or 500℃ fracture in a predominantly ductile failure mode due to the formation of adiabatic shear bands.

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