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Temperature- and Strain-Rate- Dependent Mechanical Response of a 316 Stainless Steel

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ABSTRACT
A comprehensive study of the mechanical response of a 316 stainless steel is presented. The split-Hopkinson bar technique was used to evaluate the mechanical behavior at dynamic strain rates of 500 s^{-1}, 1500 s^{-1}, 3000 s^{-1} and temperatures of 22°C and 300°C under tension and compression loading, while the Drop-Hopkinson bar was used to characterize the tension behavior at an intermediate strain rate of 200 s^{-1}. The experimental results show that the tension and compression flow stress is reasonably symmetric, exhibits positive strain rate sensitivity, and is inversely dependent on temperature. The true failure strain was determined by measuring the minimum diameter of the post-test tension specimen. The 316 stainless steel exhibited a ductile response, and the true failure strain increased with increasing temperature and decreased with increasing strain rate.

Keywords: Stainless steel, Strain rate effect, Temperature sensitivity, Intermediate strain rate

INTRODUCTION

Stainless steels have been of great interest to the automotive, aerospace, defense, medical, and nuclear power industries for its excellent corrosion resistance, machinability, and mechanical properties. In these applications, it is desirable for stainless steels to be resistant against external impact from low-speed accidental crash to explosion, and this requires understanding of the mechanical response under different loading environments. The 300 series austenitic stainless steels are non-magnetic when annealed and can only be strengthened through cold working. They have a face centered cubic (FCC) crystal structure that is attained through alloying elements such as nickel, manganese, and nitrogen [1]. This allows them to exhibit excellent strength and ductility at both cryogenic and elevated temperatures.

The mechanical response of austenitic stainless steels under different loading conditions have been investigated by several research groups over the years [2-4]. Byun et al. [2] studied the tension response of several annealed and cold worked austenitic stainless steels at a quasi-static strain rate of 10^{-3} s^{-1} and over a temperature range of -150°C to 450°C. They found the material deformation became increasingly more localized as the temperature increased from -100°C to 200°C. Lee et al. [3] investigated the compression response of 316L stainless steel over a dynamic strain rate range of 1000 s^{-1} to 5000 s^{-1} and temperature range of 25°C to 800°C. The specimens were more liable to fracture at higher strain rates (i.e. 5000 s^{-1}) and lower temperatures (i.e. 25°C & 200°C), and the failure behavior was dominated by the formation of adiabatic shear bands. Jin et al. [4] studied the tension behavior of a 304L-VAR stainless steel at ambient temperature and at every order of magnitude of strain rate from 10^{-3} s^{-1} to 3500 s^{-1}. They were able to bridge the gap between the quasi-static and dynamic loading regimes by performing experiments at intermediate strain rates using the fast MTS and Drop-Hopkinson bar.

The objective of the current work is to characterize the tension and compression behavior of a 316 stainless steel at temperatures of 22°C and 300°C, and at intermediate and dynamic strain rates using the Drop-Hopkinson bar and split-Hopkinson bar technique, respectively. The effects of strain rate and temperature on the mechanical response of a 316 stainless steel are determined. The experimental data obtained from this study will be used to develop, calibrate, and validate a material model that can be used for various applications in the automotive, aerospace, defense, medical, and nuclear power industries.

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EXPERIMENTAL DETAILS
An annealed 316 stainless steel was investigated in this study. The alloy was obtained from Marco Steel & Aluminum and the chemical composition from the supplier is listed in Table 1. The tension and compression specimens were obtained from a cold-drawn round bar with a diameter of 25.4 mm. The tension specimens had a diameter of 3.18 mm and gage length of 6.35 mm for a L/D ratio of 2. The compression specimens had a diameter of 6.35 mm and length of 3.18 mm for a L/D ratio of 0.5. The specimen was designed to ensure uniform deformation and to reduce the longitudinal and radial inertia effects during a dynamic experiment.

The split-Hopkinson pressure bar was used to perform dynamic uniaxial tension and compression experiments at nominal strain rates of 500 s^{-1}, 1500 s^{-1}, 3000 s^{-1}. A schematic of the tension and compression setups are shown in Figs. 1 & 2 and presented in detail in [5] and [6], respectively. The tension setup at 22°C includes a high-speed laser extensometer, as shown in Fig. 1(a). The laser beam was split into two separate high-speed photodetectors to measure the displacement histories of the incident and transmission bar ends, respectively [7]. The tension experiments at 300°C were performed using a thermal chamber and a thermocouple was placed on the surface of the specimen to measure the temperature, as shown in Fig. 1(b). The deformation over the gage section for all tension specimens were corrected using the procedures presented in [8].

Uniaxial tension experiments in the intermediate strain rate range were conducted at 22°C using the Drop-Hopkinson bar, as shown in Fig. 3. The procedures for the Drop-Hopkinson bar are presented in detail in [9]. The same methods were used to measure the displacement histories of the bars and to correct the specimen deformation over the gage section.

Table 1 Reported chemical composition of 316 stainless steel

C	Co	Cr	Cu	Mn	Mo	N	Ni	P	S	Si	Fe
0.015	0.41	16.53	0.36	1.29	2.024	0.030	10.51	0.031	0.026	0.27	Remainder

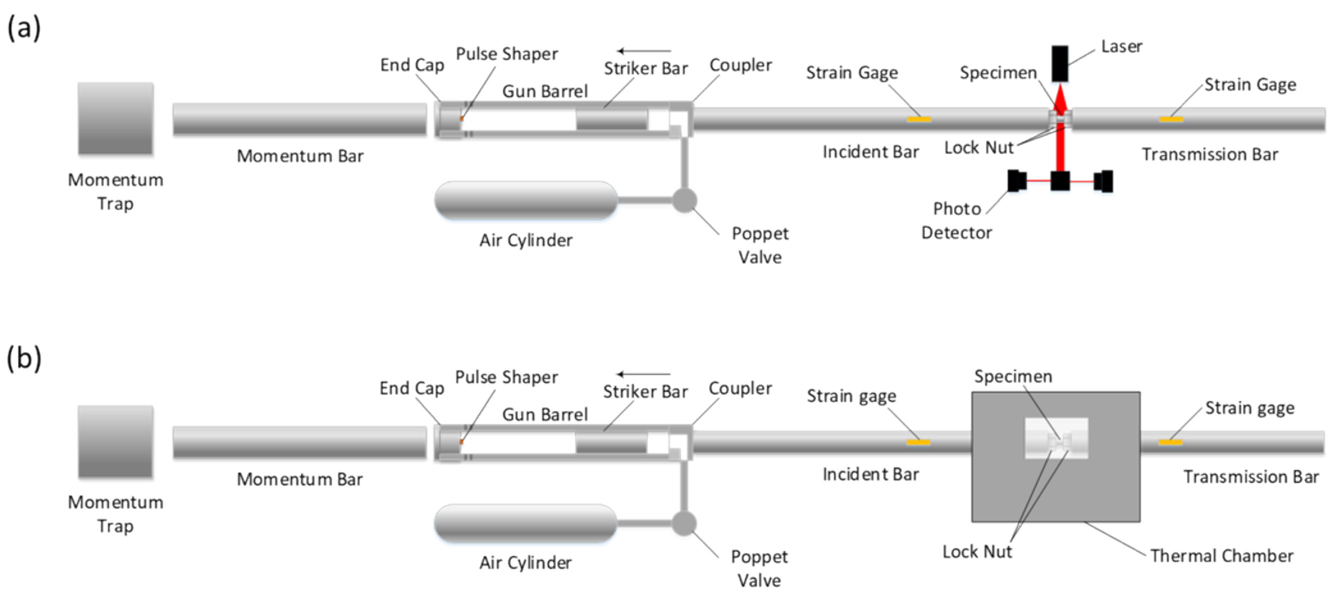

Fig. 1 Schematic view of the tension split-Hopkinson pressure bar setup for experiments at (a) 22°C and (b) 300°C

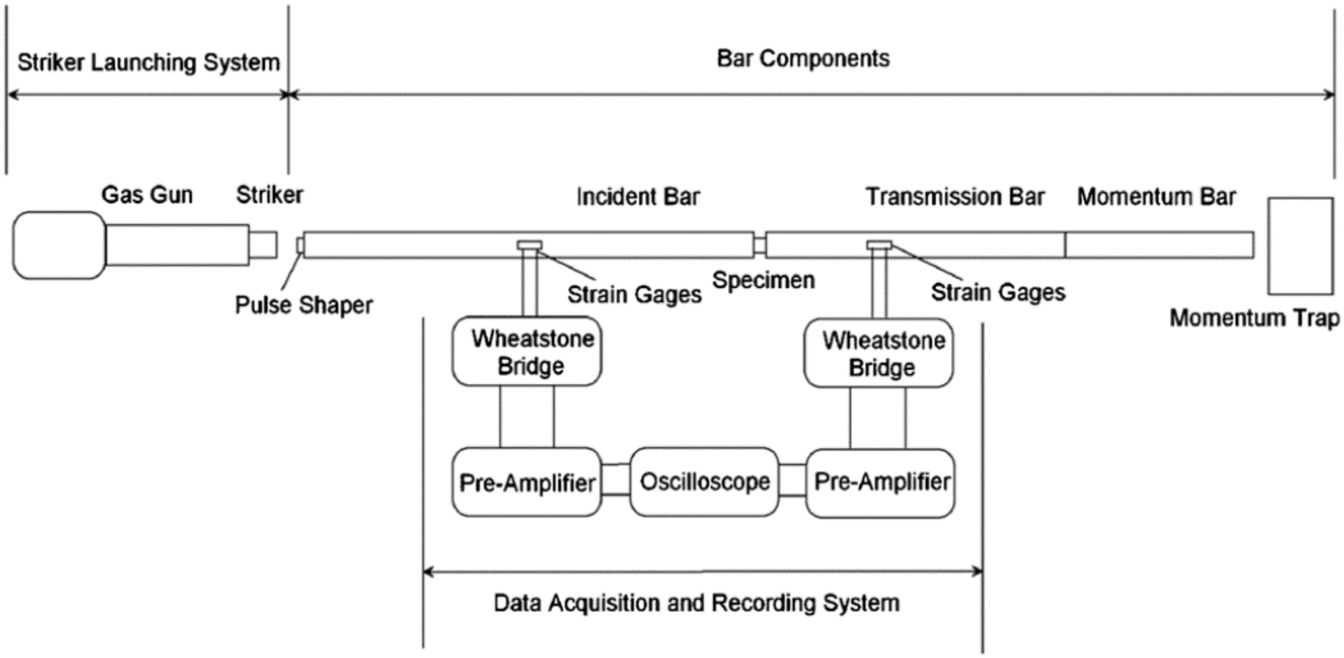

Fig. 2 Schematic view of the compression split-Hopkinson pressure bar setup [6]

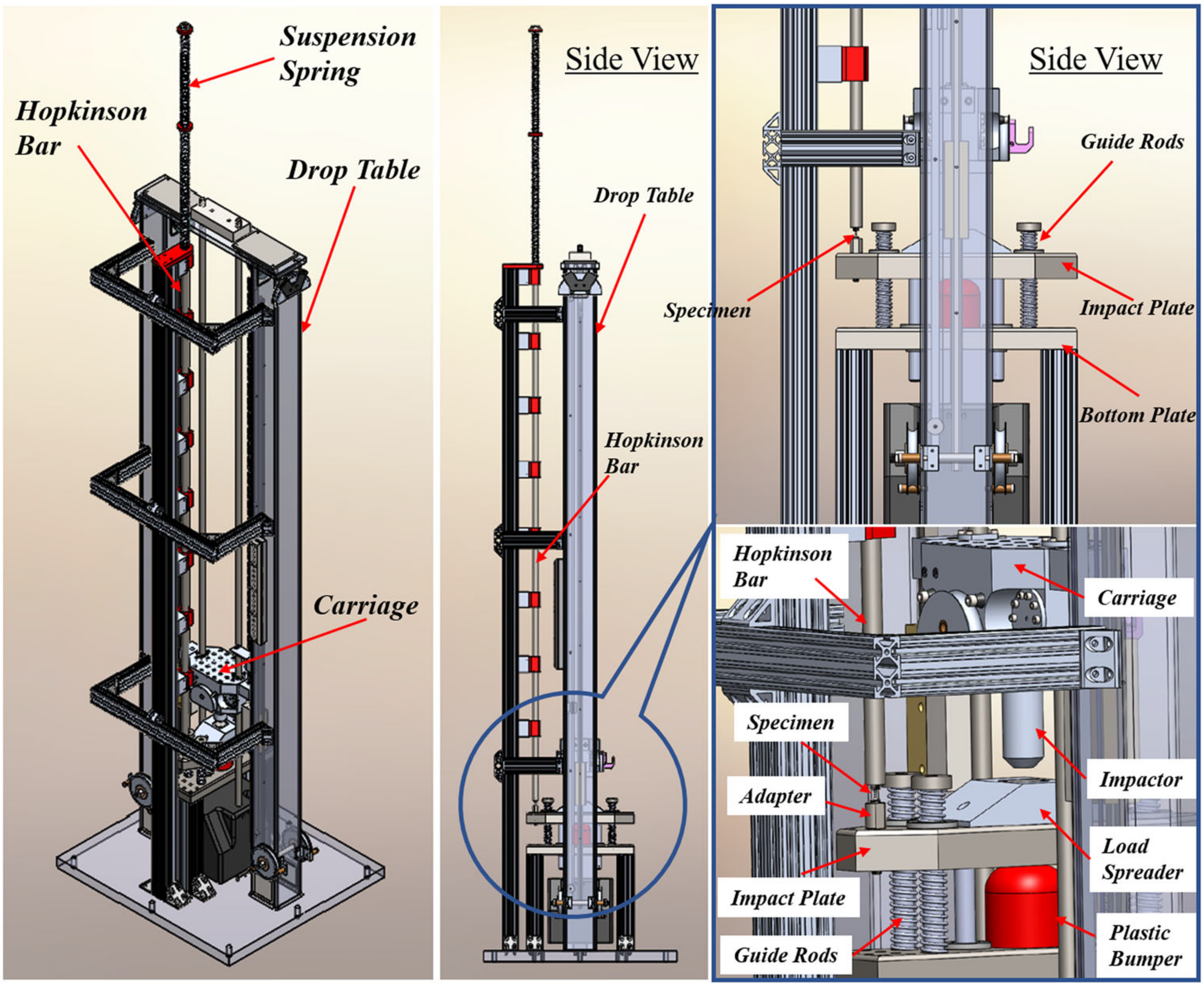

Fig 3 Schematic view of the Drop-Hopkinson bar setup [9]

RESULTS AND DISCUSSION

The mechanical behavior of a 316 stainless steel is characterized under uniaxial tension and compression loading at 22°C and 300°C, and at various strain rates. At least three specimens were tested at each experimental condition and the average engineering and true stress-strain curves are presented in Figs. 4 & 5, respectively. It is noted that, due to the limited duration of loading, the stress-strain curves at 22°C/520 s^{-1} and 300°C/530 s^{-1} shown in Fig. 4(a) do not represent specimen failure. The true stress-strain curves in tension, as shown in Fig. 5(a), are plotted up to the onset of necking.

The tension and compression flow stress exhibits positive strain rate sensitivity that varies with strain and is inversely dependent on temperature. At 22°C, increasing strain rate results in a ~10% increase in the 0.2% tensile yield stress and a ~7% increase in ultimate tensile stress. At 300°C, deformation becomes more localized as indicated by a decrease in engineering strain to failure, and material behaviors such as yield stress, ultimate tensile stress, and strain hardening rate are reduced. Fig. 6 compares the tension and compression response at 22°C under dynamic loading at the same strain rates. The results show reasonable symmetry in flow stress.

Fig. 7 shows the effect of strain rate on the true failure and strain at onset of necking. The true failure strain is determined by measuring the minimum diameter of the post-test specimen. The strain at onset of necking is determined from the engineering strain at the ultimate tensile stress, which is then converted to true strain. Increasing temperature from 22°C to

300°C results in an increase in failure strain and decrease in strain at onset of necking. In addition, the true failure strain decreases with increasing strain rate, though the strain at onset of necking remains somewhat constant.

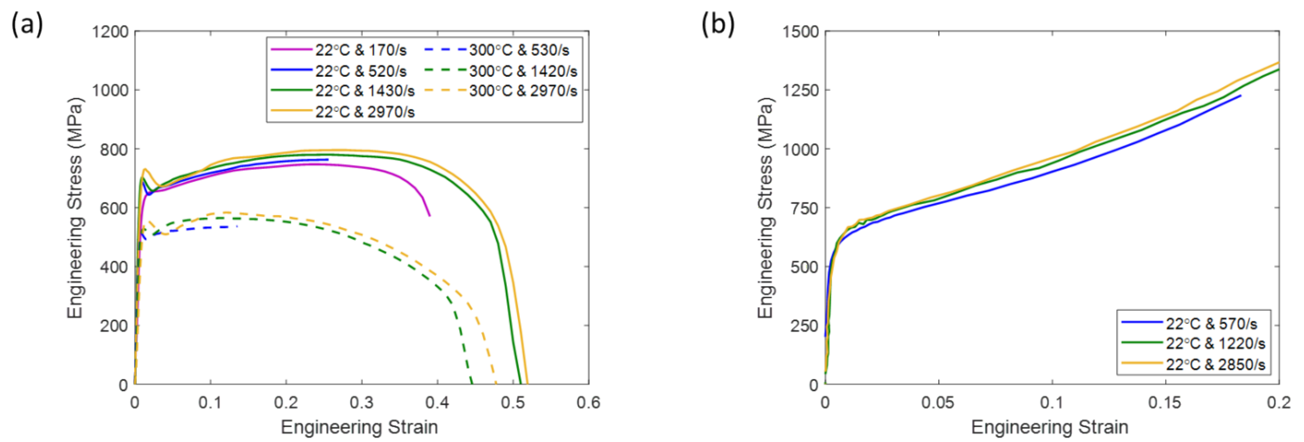

Fig. 4 Engineering stress-strain behavior of 316 stainless steel at various temperatures and strain rates under (a) tension and (b) compression loadings

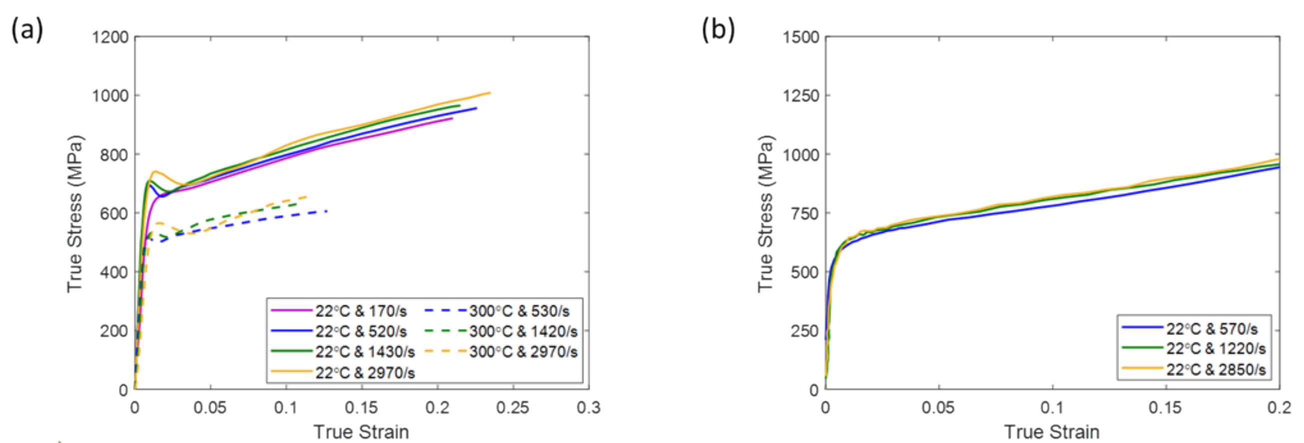

Fig. 5 True stress-strain behavior of 316 stainless steel at various temperatures and strain rates under (a) tension and (b) compression loadings

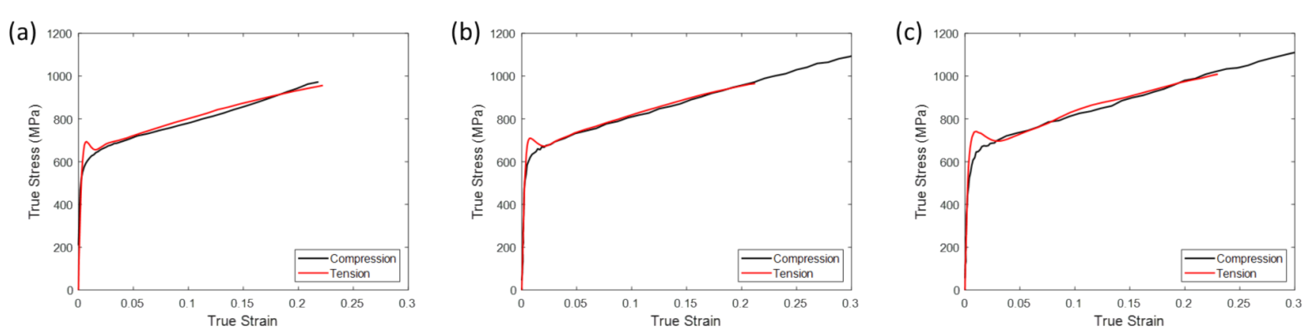

Fig. 6 Comparison of the true tension and compression behavior of 316 stainless steel at 22°C and at nominal strain rates of (a) 500 s^{-1}, (b) 1500 s^{-1}, (c) 3000 s^{-1}.

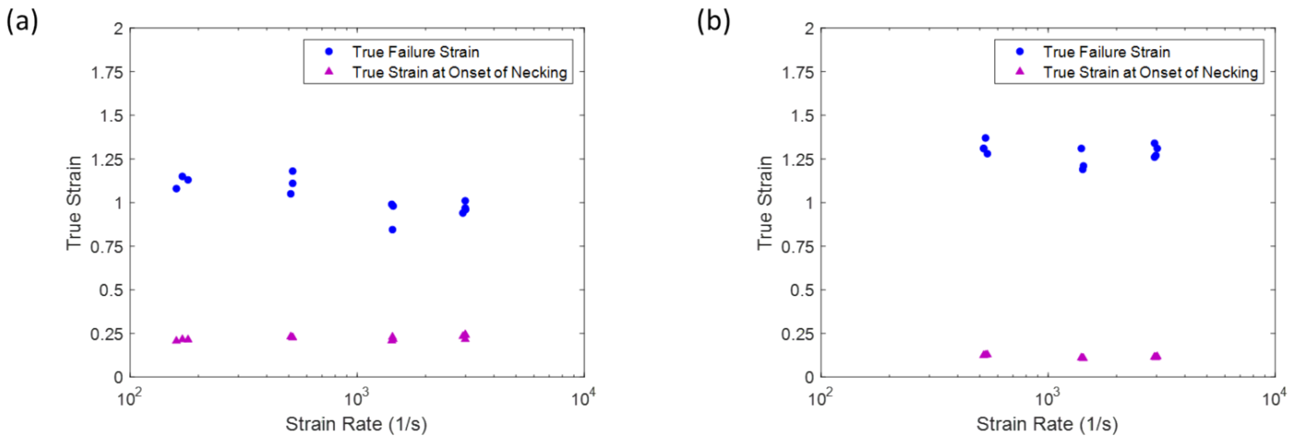

Fig. 7 Strain rate effect on the failure strain and strain at onset of necking at (a) 22°C and (b) 300°C.

CONCLUSION

In this study, the mechanical response of a 316 stainless steel is characterized at 22°C and 300°C, and at various strain rates between 200 s^{-1} and 3000 s^{-1}. The experimental results show that the tension and compression flow stress is reasonably symmetric, exhibits positive strain rate sensitivity, and is inversely dependent on temperature. The true failure strain in tension is determined by measuring the minimum diameter of the post-test specimen. The 316 stainless steel is very ductile, and the true failure strain increased with increasing temperature and decreased with increasing strain rate.

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