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Techniques for Testing 304L Stainless Steel over a Wide Range of Temperatures

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ABSTRACT

Various techniques and heating methods have been employed to characterize the compressive and tensile behavior of 304L stainless steel over a wide range of test temperatures. Depending on the test temperature, the experimental apparatus required to produce uniform temperatures in the specimens varied significantly. Compression experiments imposed additional difficulty in achieving a uniform temperature throughout the specimen, but were attainable using secondary heating of the test platens. The 304L material was characterized in tension at quasi-static rates and in compression over an extensive range of strain rates to the very high strain rate regime. Strain rate effects were experimentally determined and a reversal in the strain rate effect was discovered at some temperature and strain rate combinations. Dynamic recrystallization was observed at some temperature and strain rate regimes.

INTRODUCTION

304L stainless steel has historically been of significant interest to Sandia National Laboratories due to its numerous attractive properties such as high ductility, fracture toughness, corrosion resistance and resistance to hydrogen embrittlement. Hence, it has been utilized extensively in many of the Laboratories' components and systems. Extensive characterization of the mechanical behavior of 304L stainless steel has been completed over the past few years for a variety of reasons: development of a validated multi-stage forging process for warm working of reservoirs [1, 2], development of a recrystallization material model [3], understanding and solution of various thermal mechanical problems [4], and modeling component response to thermal changes and large deformations [5].

304L stainless steel is highly strain rate and temperature dependent. Strain rates of interest for our studies ranged from quasi-static through several orders of magnitude to dynamic strain rates that are only achievable on a Hopkinson bar apparatus. Several types of experiments were used to completely characterize the material behavior. However, the temperature and strain rate dependence were examined with tension or compression experiments, depending on the study and the strain level required. In all studies, the 304L stainless steel specimens were machined from material removed from the same lot of 6.35 cm (2.5 in.) bar stock, followed by a vacuum anneal at 1000ºC, for a time that was dependent on the specimen size.

Several test frames were used to span the experimental regime, including two 9 Kg (20 Kip) MTS frames, a 26.8 Kg (50 Kip) MTS frame, a 100 Kg (220 Kip) MTS frame that operates to 23 cm/s (9 in/s), a 55.7 Kg (100 Kip) MTS frame and a split Hopkinson pressure bar (SHPB) [6-8]. Specimens tested up to 1000°C were typically heated in a three-zone resistance furnace; each set of experiments used a furnace that was matched by bore size and power to the specific fixtures and specimen size. Compression experiments required uniform heating over the entire specimen length. This is much more difficult to obtain than in a tensile specimen that has a reduced gage section, due to significant heat transfer that occurs at the specimen ends. This heat loss is compensated for by a combination of secondary platen design and independently heated push rods. Specimens tested above 1000°C were heated by induction heating. Compression experiments in above 1000°C required utilizing a graphite susceptor that was specifically designed to the account for the heat transfer characteristics of the frame, fixtures and specimen; additionally heated push rods were again required. The techniques and results for testing 304L stainless steel in tension and compression is presented in the following sections.

TENSILE EXPERIMENTS

All tensile experiments were conducted in extensometer control to produce a strain rate of 0.001/s on a 26.8 Kg (50 Kip) MTS test frame using Teststar control. The specimen diameter was 0.9 cm (0.35 in.), the three-zone resistance furnace was used for tests above 25°C. High temperature threaded couplers coated with high temperature thread lubricant were used to interface each specimen to the pull rods to allow heating of the entire specimen length. Temperature was monitored with type K thermocouples at each end of the reduced gage section. Photographs of the test system, and room temperature and 800°C tensile specimens just after failure are shown in Fig.1.

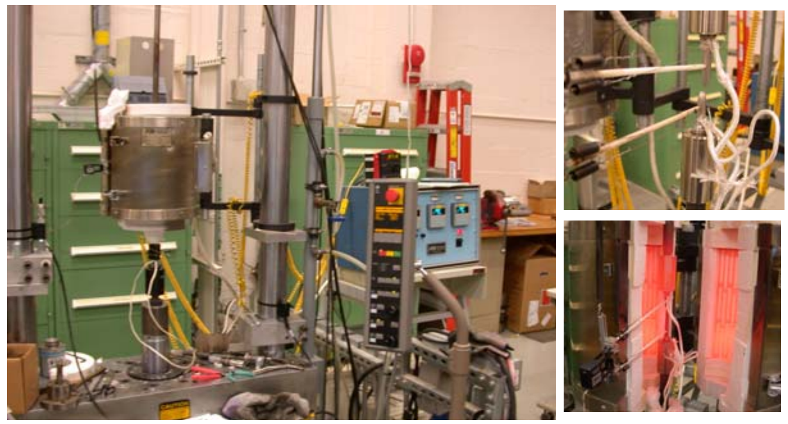

Fig. 1 Tensile experimental setup and failed specimens.

Tensile experiments were conducted at several temperatures between 25°C and 800°C; the results for all temperatures are shown in Fig. 2. Between 600°C and 800°C, the stress-strain curves are indicative of recrystallization occurring in the 304L microstructure. Also noticeable is the transition above 700°C to much larger elongation.

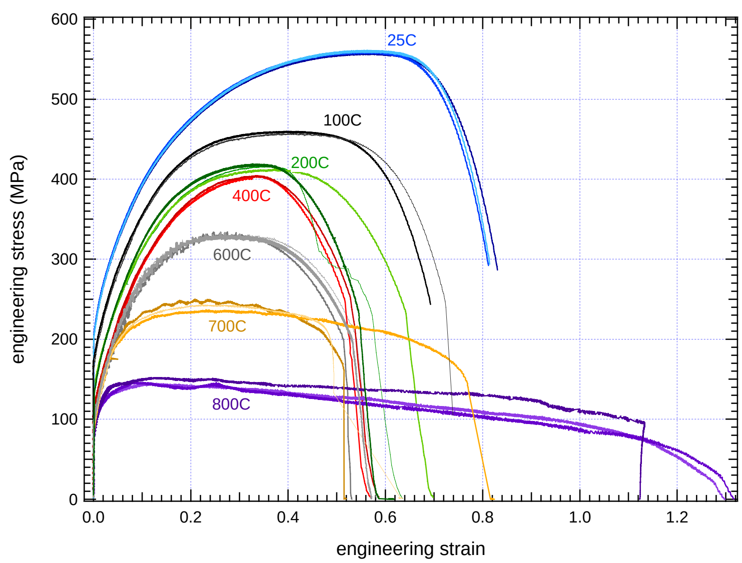

Fig. 2 304L stainless steel tensile results.

COMPRESSION EXPERIMENTS

Compression experiments were conducted to characterize the 304L stainless steel to large strain levels. Frictional effects at the interface between the specimen ends and the test fixtures were minimized to achieve uniformly strained specimens, yielding meaningful material data to the large strain levels. Friction was minimized through specimen design that incorporated various grooved end surface geometries, along with appropriate selection of lubrication for each test temperature. The proper combination allows the material at the ends of the compression specimen to radially expand during the axial straining of the specimen, as shown in Fig. 3. End grooves were filled with a solid $MoSi_2$ lubricant for 25°C experiments and a liquid water-based glass suspension Deltaglaze 151 material for test temperatures 650°C and higher. Intermediate temperatures utilized Teflon sheet and aluminum sheet of various thicknesses as lubrication media. Along with a variation of groove geometry, this produced very uniformly strained specimens with no evidence of barreling.

Fig. 3 Top and side view of 304L specimens compressed to 70% true strain.

Compression experiments were conducted in true strain rate control, typically to 70% true strain. Tests with strain rates up to 10/s were conducted on various MTS test frames, depending on the specimen geometry, strain rate and test temperature. The specimen diameters were 0.76 cm (0.3 in.) and 1.9 cm (0.75 in.) for test temperatures below and above 1000°C, respectively. Photographs of the experimental setup for intermediate test temperatures (25°C to 650°C), high temperatures (815°C to 982°C) and near-melt temperatures (>1000°C) are shown in Fig. 4-5. Three-zone resistance furnaces were used for testing below 1000°C. Induction heating was required to reach temperatures above 1000°C, which utilized a floating, differential graphite susceptor designed to introduce heat to the specimen ends to compensate for conductive and convective heat losses. For high and near-melt test temperatures, programmable, independently heated push rods were also used to assist in obtaining uniform heating along the entire specimen lengths. Specimen temperatures were monitored with type K thermocouples. Testing techniques for higher rate tests conducted on the SHPB are described elsewhere [8].

Fig. 4 Compression setup on 55.7 Kg (100 Kip) MTS test frame for intermediate temperatures.

At each temperature, compression experiments were conducted at several strain rates. Fig. 6 illustrates the strain rate dependence of 304L stainless steel at two of the temperatures, 871°C and 982°C. The compression data are compared by temperature in Fig. 7. For three strain rates, 0.0001/s, 0.01/s and 0.1/s, several temperatures are shown together. The data in Fig. 8 illustrate a strain rate reversal effect that occurred in 304L stainless steel at two of the test temperatures, 427°C and 538°C. Note that at these temperatures and strain rates, an increase in strain rate resulted in lower compressive strengths, the opposite of what is expected and seen at all other temperatures and strain rates studied in this material thus far.

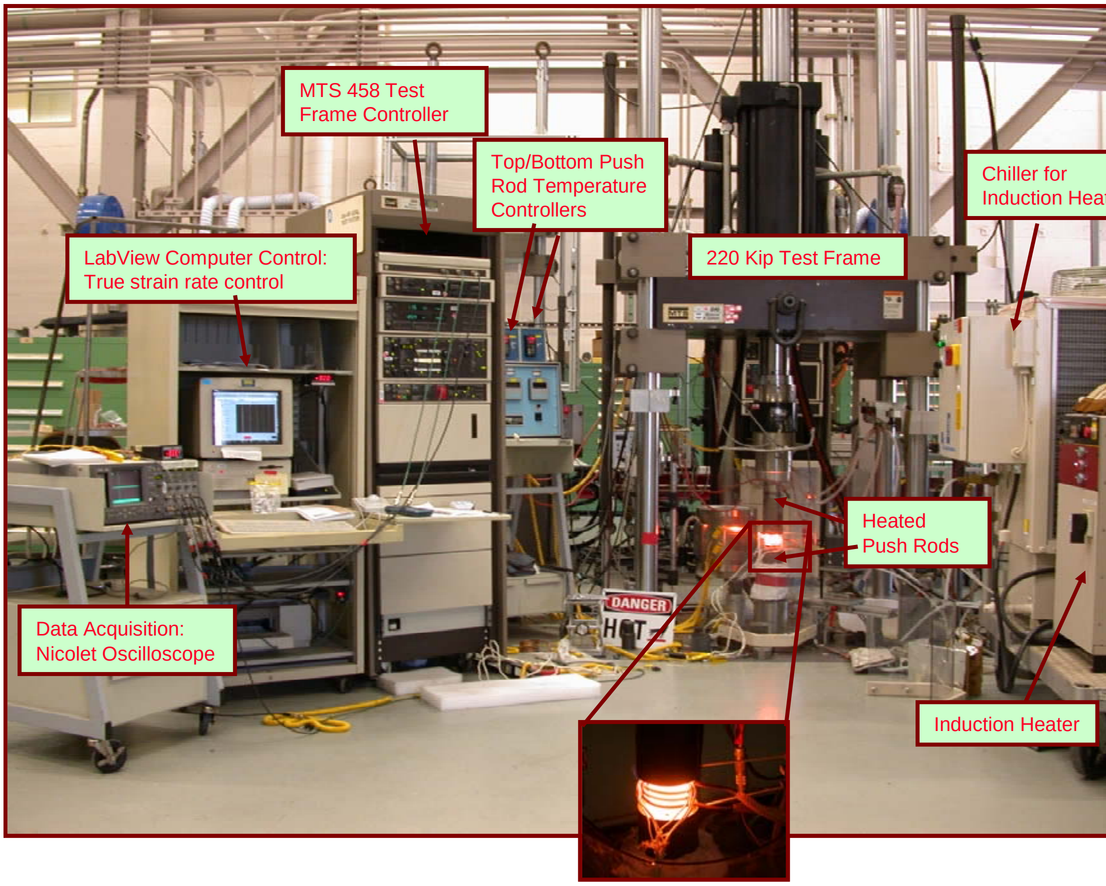

Fig. 5 Compression setup on 100 Kg (220 Kip) MTS test. High temperature tests used a three-zone furnace, near-melt temperature tests used the induction heating system as shown.

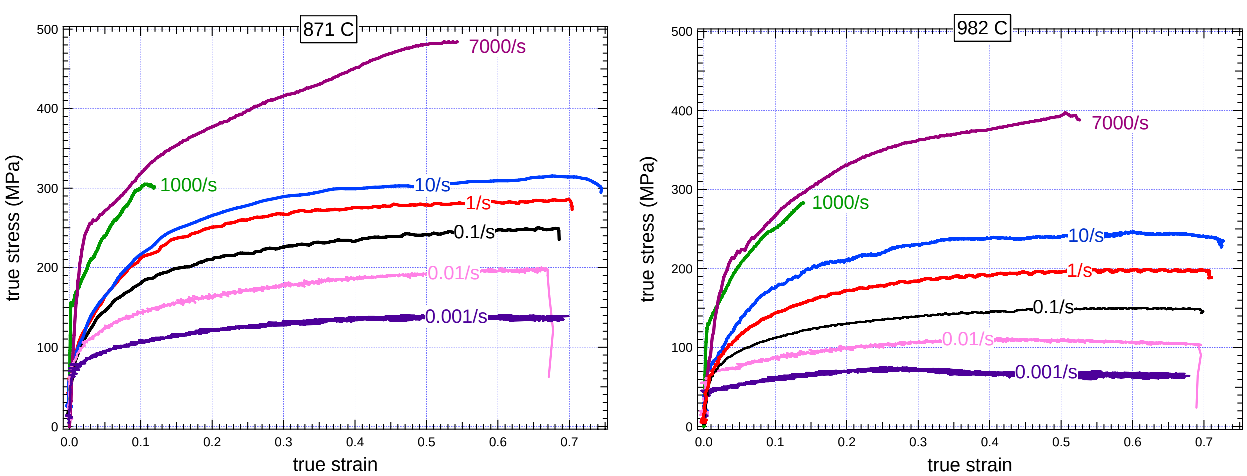

Fig. 6 Strain rate effects in compression at 871°C and 982°C.

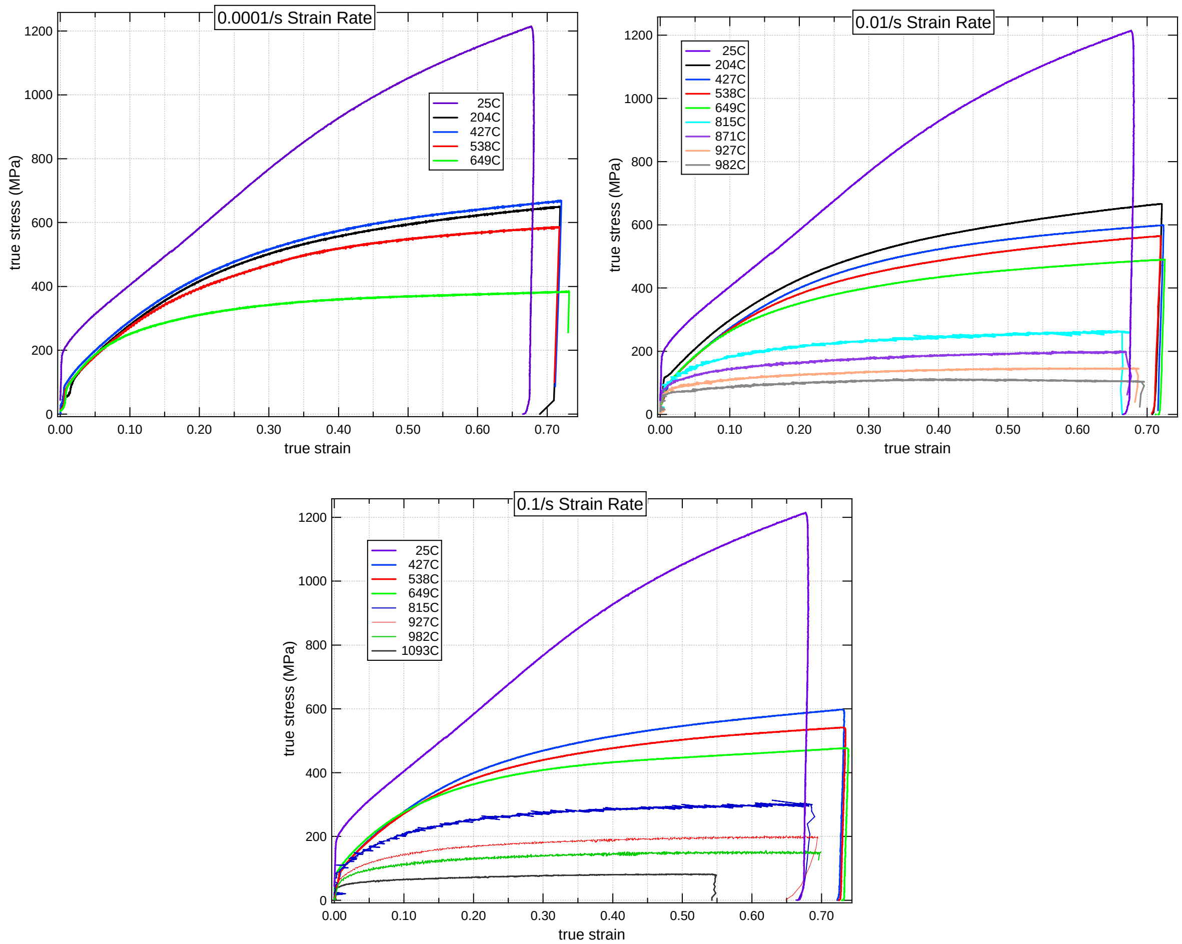

Fig. 7 Effect of temperature on compression at 0.0001/s, 0.01/s and 0.1/s strain rates.

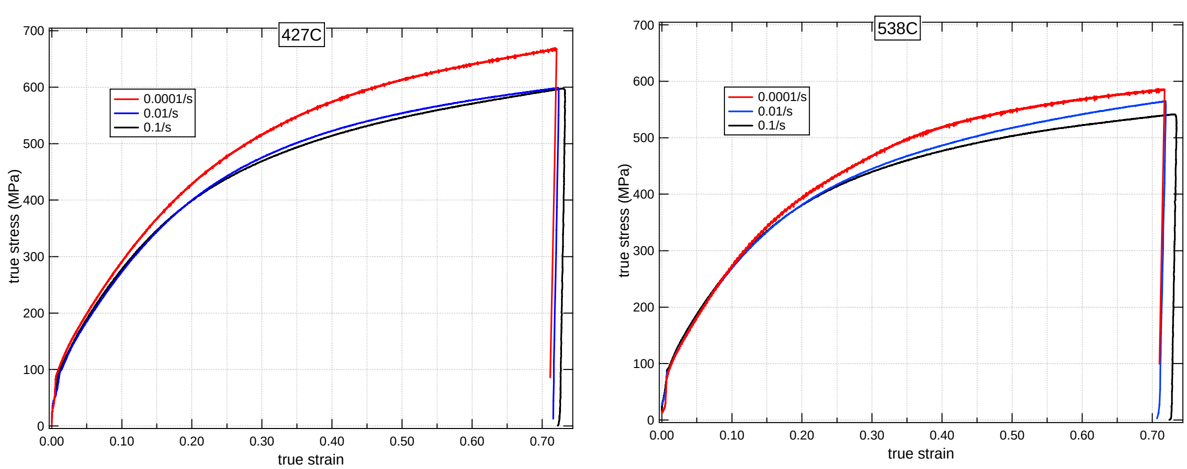

Fig. 8 Strain rate reversal effect in 304L stainless steel.

CONCLUSIONS

Several techniques and methods for characterizing the tensile and compressive behavior of 304L stainless steel over a range of temperatures from 25°C to 1177°C have been described. Achieving uniform temperature distribution in the specimens was found to be absolutely critical to obtaining meaningful data. Compression specimen size, geometry and lubrication were all varied to produce excellent results in the different temperature ranges. Stress-strain curves of the 304L stainless steel were obtained at strain rates from 0.001/s to 7000/s. SHPB experiments are continuing to allow further development of a microstructural evolution and recrystallization model.

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