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Dynamic High-temperature Compressive Response of A 304L Steel

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ABSTRACT

A split Hopkinson pressure bar (SHPB) was modified to characterize the dynamic compressive behavior of a 304L stainless steel at high temperatures. The shapes of the loading pulses were controlled such that the specimen deformed under dynamic equilibrium at constant strain rates. A heating chamber was used to heat specimen to 815 C and 927 C during dynamic experiments. In order to investigate the recrystallization and other microstructural changes, the SHPB was also modified to load the specimen only once during a test. Moreover, the specimens were quenched 6 and 30 seconds after the dynamic loading was applied to the specimen. Dynamic compressive stress-strain data at high temperatures for the 304L alloy were experimentally obtained.

INTRODUCTION

304L stainless steel has been widely used in industrial applications because of its excellent corrosion resistance, machinability, weldability, and formability. In these applications, the stainless steel is often subjected to high-temperature and/or high-rate loading during machining and forming. The high rate of loading and high temperature may induce microstructural changes. Lee and Lin [1] conducted high-rate testing of the 304L stainless steel and found that the morphologies and characteristics of both dislocation and α' martensite are sensitive to loading conditions. Greater dislocation density, more shear bands and α' martensite transformation were observed at high strain rates and large deformation [1]. Studies have been completed at various temperatures to intermediate strain rates [2-3]. However, not many investigations of high-rate response at high temperatures have been done due to experimental difficulties. The usual method of high-temperature experiment by using the SHPB has been to enclose the specimen and a portion of the bars within a furnace [4]. This setup allows heat conduction through the metallic bars, leading to a temperature gradient along the bars. When the temperature is high, the effects of a temperature gradient along the bars on the wave velocity and the elastic modulus have to be corrected [5]. Frantz et al. [5] designed a vacuum furnace for high-temperature SHPB experiments. In their design, the specimen is heated within the furnace; whereas the pressure bars, which are outside of the furnace, are separated from the specimen. When the desired specimen temperature is achieved, the pressure bars are pushed into the furnace to sandwich the specimen by driving screws with an electric motor. Lennon and Ramesh [6] used an air-cooled infrared spot heater to heat the specimen which was not in contact with the pressure bars either before test. There was an air gap between the bars and the specimen during heating. The pressure bars were then moved to contact the specimen by an electropneumatic actuation system. The bars were in contact with the specimen for tens to hundreds of milliseconds before compression of the specimen began, resulting in an inevitable decrease of the specimen temperature. This decrease should be minimized to maintain the specimen at the desired temperature during the test.

In a high-temperature SHPB experiment, the fundamental requirements for a valid SHPB experiment still need to be satisfied. For example, the specimen must be in dynamic stress equilibrium and it is desirable to deform at a nearly constant strain rate to identify the strain rate level during test. In order to correlate the loading and temperature conditions to microstructural changes in the specimen, the specimen is required to be loaded only once, which is not automatically achieved in a conventional SHPB experiment. The SHPB has recently been modified to facilitate a single loading on the specimen [7]. In this study, we used this modified SHPB to conduct dynamic compressive experiments on the 304L stainless steel at the nearly constant rate of 3000 s^{-1} at two temperatures, 815 C and 927 C. The specimens which were subjected to single loading at the constant rate were reserved after quenching for further microstructural investigation.

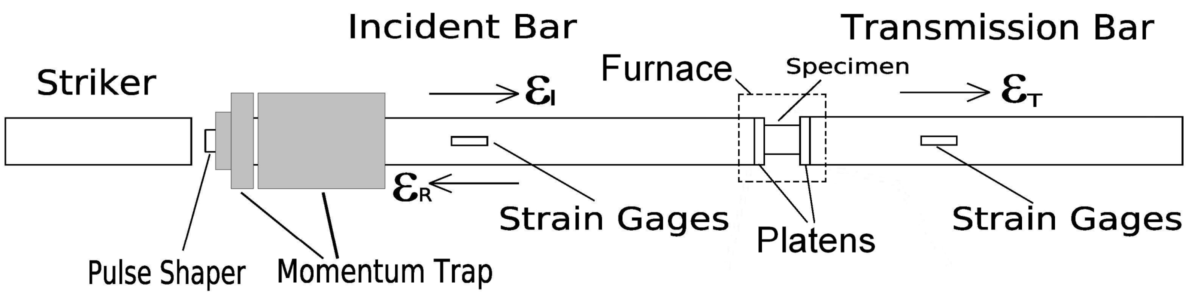

Fig. 1 A schematic of the modified SHPB.

DYNAMIC EXPERIMENTS

The SHPB technique for dynamic high-temperature characterization is schematically shown in Fig. 1. This modified SHPB is the same as a conventional SHPB except for the pulse shaper, the momentum trapping system, and the associated heating and temperature control system. A pulse shaper is attached to the impact end of the incident bar to modify the profile of the incident pulse. Through proper pulse shaping design, including the striking speed and the pulse shaper material and dimensions, the incident pulse can be modified to facilitate constant strain rate deformation under dynamic stress equilibrium. The pulse shaping techniques have been recently discussed and documented [8]. As shown in Fig. 1, the momentum trapping system consists of a flange screwed on the impact end of the incident bar and a rigid mass through which the incident bar passes. The most important issue to successfully trap the additional momentum is to set up an appropriate gap between the flange and the surface of the rigid mass. In a conventional SHPB experiment, when the incident bar is impacted by the striker, an incident loading pulse is generated and propagates towards the specimen through the bar. This pulse is reflected back into the incident pulse as a tension reflected pulse and the rest transmits into the transmission bar through the specimen. The tension reflected pulse will be reflected back again at the free impact end of the incident bar as a secondary compression pulse which loads on the specimen again. However, in the modified SHPB (Fig. 1), the secondary loading can be trapped through the precisely controlled gap between the flange and the rigid mass. The gap should close before the secondary loading pulse arrives such that the momentum brought by the secondary loading pulse is transferred to the rigid mass instead of the bar system. The width of the preset gap between the flange and the rigid mass, *d*, should satisfy

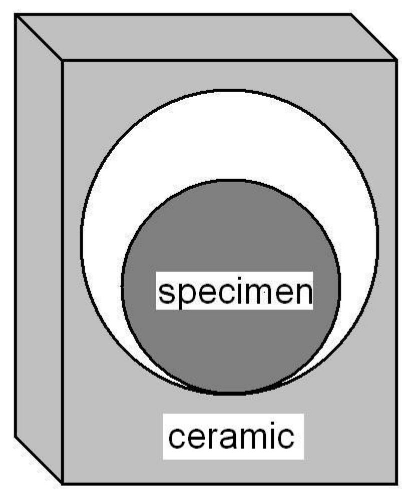

Fig. 2 Specimen configuration

$$d = C_0 \int_0^{t_0} \varepsilon_i(t) dt, \quad (1)$$

where $\varepsilon_i(t)$ is the incident bar strain history; t_0 is the loading duration of the incident pulse; and C_0 is the elastic wave speed in the bar material. In this study, the 19-mm-diameter pressure bars are made of a C350 maraging steel. Like the work by Albert and Gray [9], a 304L stainless steel specimen was individually heated in the temperature-controlled furnace while the outside pressure bars were at room temperature before each test. The specimen is required to be reliably supported inside the furnace and align with the bar system during heating. In this study, the 304L stainless steel specimen was supported by a light-weight, low-strength ceramic board with a hole, as shown in Fig. 2. This ceramic board can work at the temperatures as high as 1760 C. The strength of the ceramic board is too low to significantly affect the measurement of flow stress of the 304L stainless steel even though both ceramic board and the specimen are compressed during experiment. However, the lateral confinement by the ceramic board may induce the specimen into a 3-D stress state. This 3-D stress state provides an additional component in the measurement of axial stress. Figure 3 shows a comparison of the dynamic stress-strain curves of the 304L stainless steel without and with confinement. When the ceramic board was used to confine the specimen, two diameters of the hole in the ceramic board were selected for experimental verification: one is the same diameter as the specimen and another one is bigger than the specimen diameter. All experiments were conducted at room temperature and the strain rate is 3000 s^{-1}. When the hole in the ceramic board has the same diameter as the specimen diameter, leaving no gap between the specimen and the ceramic board, the stress-strain curve is observed to be a little higher than the curve without confinement, indicating the effect of 3-D stress state in specimen that needs to be corrected. When the hole is bigger than the specimen diameter, only the bottom of the specimen was in contact with the ceramic board. The stress-strain curve overlaps with the curve without confinement. Therefore, the design of the ceramic board with bigger hole is appropriate to support the specimen and it is not necessary to correct for stress state effects. In addition, this overlapping also indicates that, due to the low strength of the ceramic board, its existence and axial compressive loading during the experiment do not affect the measurement of axial stress in specimen.

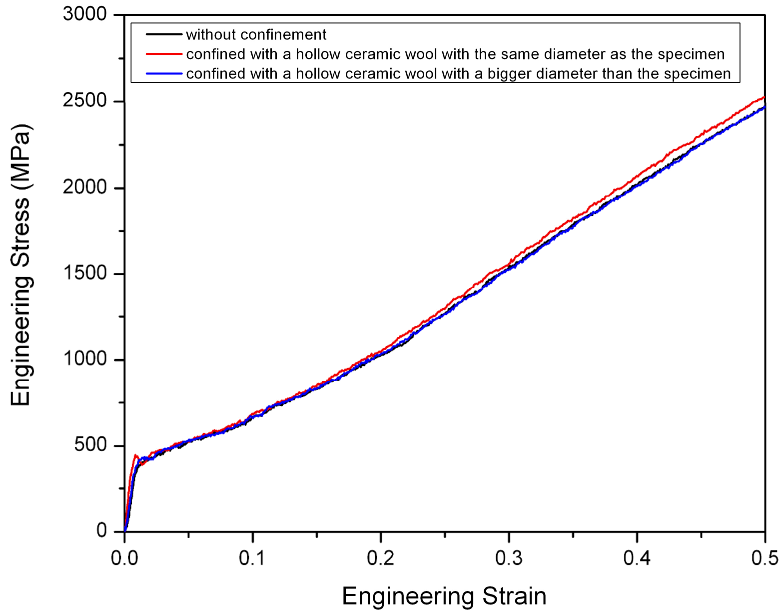

Fig. 2 Comparison of stress-strain curves of the 304L steel without confinement and confined with hollow ceramic boards that have the same diameter and a bigger diameter than the specimen.

Therefore, the modifications to the SHPB shown in Fig. 1 are capable of conducting dynamic compression experiments on the 304L stainless steel at high temperatures. Besides the constant strain rate deformation and dynamic stress equilibrium through the pulse shaping techniques, the modified SHPB also ensures a single loading on the specimen during experiments through the momentum trapping system, making it realistic to investigate the changes of microstructure in individual specimens due to dynamic loading at high temperatures. In order to study the effect of quenching time on recrystallization and grain growth, the specimens were quenched at either 6 or 30 seconds after the dynamic loading of the specimen. The experimental results will be presented in the SEM conference which will be held in Springfield, MA, June 3-6, 2007.

CONCLUSIONS

The SHPB was properly modified to conduct dynamic compressive experiments on a 304L stainless steel at high temperatures. Pulse shaping techniques were used to facilitate constant strain rate deformation under dynamically equilibrated stress in specimen. A momentum trapping system was also employed to ensure a single loading on the specimen during experiments. The specimens were quenched after 6 or 30 seconds after dynamic testing for the purpose of investigating microstructural changes in the 304L stainless steel material due to dynamic recrystallization. The pressure bars were separated from the specimen, which was supported by a hollow ceramic board during heating. This hollow ceramic board support has been verified not to affect the dynamic response of the steel specimen. Dynamic stress-strain curves of the 304L stainless steel were obtained at the strain rate of 3000 s^{-1} at two temperatures, 815 C and 927 C.

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