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Dynamic Compressive Response of Wrought and Additive Manufactured 304L Stainless Steels

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Abstract. Additive manufacturing (AM) technology has been developed to fabricate metal components that include complex prototype fabrication, small lot production, precision repair or feature addition, and tooling. However, the mechanical response of the AM materials is a concern to meet requirements for specific applications. Differences between AM materials as compared to wrought materials might be expected, due to possible differences in porosity (voids), grain size, and residual stress levels. When the AM materials are designed for impact applications, the dynamic mechanical properties in both compression and tension need to be fully characterized and understood for reliable designs. In this study, a 304L stainless steel was manufactured with AM technology. For comparison purposes, both the AM and wrought 304L stainless steels were dynamically characterized in compression Kolsky bar techniques. They dynamic compressive stress-strain curves were obtained and the strain rate effects were determined for both the AM and wrought 304L stainless steels. A comprehensive comparison of dynamic compressive response between the AM and wrought 304L stainless steels was performed.

1 Introduction

Additive manufacturing (AM), also commonly known as 3D printing, has been increasingly utilized in many applications that include rapid prototyping and manufacturing, as well as mass customization for automobile, aerospace, construction, and defense industries. For example, Sandia National Laboratories developed a Laser Engineered Net Shaping (LENS) technology, a type of AM technology which utilizes a combination of metal powders and a laser to create metallic components designed by computer aided design (CAD) models [1]. New AM processes that are LENS-like have been recently developed to create components at much higher deposition rates. Often as AM materials are created, residual stresses may occur and grain structures may change [2], which can lead to uncertainties in the mechanical behaviour of the material. Particularly, the AM materials may be utilized in abnormal mechanical environments where the materials are subjected to impact loading. Understanding the dynamic response of the AM materials is critical for applications in terms of reliability, particularly when compared to wrought materials.

In this study, a wrought and AM processed 304L stainless steel (SS) were dynamically characterized to compare compressive stress-strain curves at various strain rates with a split Hopkinson pressure bar (SHPB) or Kolsky compression bar.

2 Materials & Experimental Procedure

The 304L SS used in this paper has been formed using a high-powered (3.8 kW) LENS-like AM process developed at Pennsylvania State University. The chemical composition of the AM 304L SS was exactly the same as that of the wrought 304L SS. The compressive specimens for the wrought 304L SS were machined in a disc shape with a diameter of 6.35 mm and a thickness of 3.175 mm along the longitudinal and transverse directions, respectively. The compressive specimens for the AM 304L had the same dimensions, but were machined in an X, Y, and Z direction, respectively. It is noted that the AM 304L specimens were treated as delivered without any additional heat treatment or annealing process. The purpose of making the compressive specimens in different directions for both wrought and AM 304L SS is to examine and compare the isotropic characteristic for both wrought and AM 304L stainless steels. In this study, we characterized the wrought 304L SS in both longitudinal and transverse directions, and the AM 304L SS in the X direction. The

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X direction refers to the travel direction of the laser during the LENS process.

The dynamic compression experiments were conducted with a Kolsky compression bar at Sandia National Laboratories. The Kolsky compression bar, also called the SHPB, was originally developed in the 1940s [3]. As shown in Figure 1, a general Kolsky compression bar set-up consists of a striker, incident bar, transmission bar, and momentum bar.

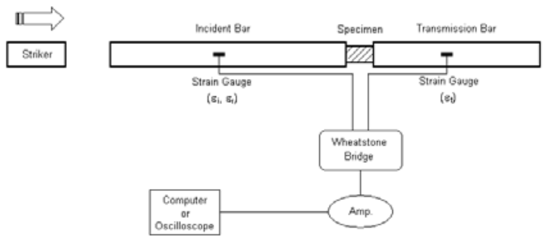

Figure 1. General Schematic of a Kolsky Compression Bar Set-Up

The striker is usually launched with a gas gun to impact the incident bar, generating a compressive stress wave (incident wave) that is recorded with the strain gages on the incident bar. When the incident wave propagates to the specimen, part of the stress wave is reflected back into the incident bar and recorded with the same strain gages due to the mismatch of mechanical impedance between the pressure bars and the specimen. The rest of the stress wave transmits into the transmission bar though the specimen and is recorded with strain gages on the transmission bar. Using one-dimensional, wave propagation analysis, the measured strain signals from the strain gages can be used to determine the dynamic behaviour of the sample,

$$\dot{\varepsilon} = -\frac{2c_0}{L}\varepsilon_r \quad (1)$$

$$\sigma = \frac{A_0}{A_s}E\varepsilon_t \quad (2)$$

where L and A_s are the original sample length and cross-sectional area ; c_0, E, and A_0 are the elastic bar-wave velocity, Young's modulus, and cross-sectional area of the bars ; $\varepsilon_r$and ε_t are the measured reflected and transmitted strain signals.

It is noted that Equations (1) and (2) are based on the assumption of stress equilibrium during dynamic loading. However, this assumption may not be automatically satisfied in conventional Kolsky bar experiments. In addition, the strain rate in the specimen may not be constant, particularly when the specimen exhibits significant work hardening behavior, which may further generate uncertainties in determining strain rate sensitivity of the material under investigation.

Pulse shaping techniques have been developed and extensively used in Kolsky bar experiments in order to minimize stress wave dispersion and create a desired loading pulse, allowing for constant strain rate deformation and dynamic stress equilibrium [4]. In this study, a double pulse shaping technique that consists of a small copper disc and a steel disc was employed.

The pressure bars used in this study were made of C300 Maraging steel and had a common diameter of 19.05 mm. The incident and transmission bars were 3658 mm and 1829 mm long, respectively. The length of the striker was varied for compression tests at various strain rates.

3 Experimental Results and Discussion

Dynamic compression tests were conducted at 2500 s^{-1}, 1500 s^{-1}, and 500 s^{-1} in the longitudinal and transverse directions for the wrought 304L SS and X direction for the AM 304L SS.

Figure 2 shows a typical set of oscilloscope records of strain gage signals on the incident bar (solid line) and transmission bar (dotted line) in a compression Kolsky bar experiment for the wrought 304L SS specimens.

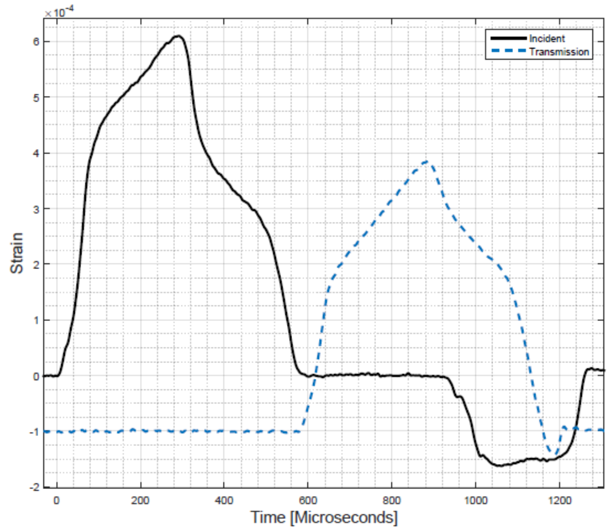

Figure 2. Typical Pulse Shaped Compression Oscilloscope Record for the Wrought 304L SS Specimens

Figure 2 clearly shows a significantly different profile in the incident wave from the conventional trapezoidal incident wave in Kolsky bar experiments, due to the use of the pulse shaping technique. This modified incident pulse generated a nearly flat reflected pulse, which represents a constant strain rate when the specimen is equilibrated.

Figure 3 shows the stress equilibrium process in the specimen.

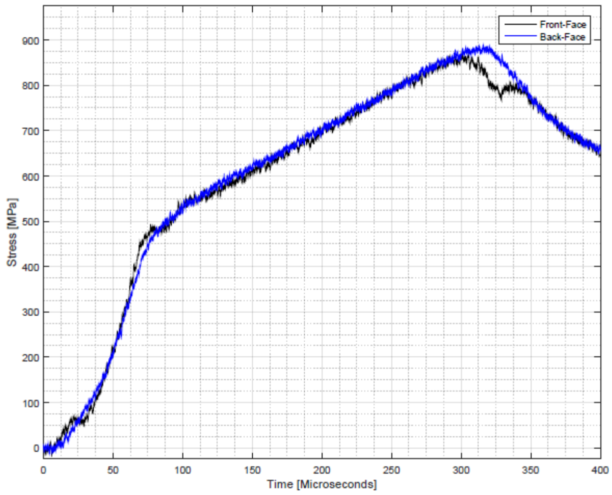

Figure 3. Sample Stress Equilibrium Plot on the Front-Face and Back-Face of the Specimen

The specimen stress at the transmission bar end (back-face) was calculated with Equation (2). The specimen stress at the incident bar end (front-face) was calculated with the 2-wave method,

$$\sigma_1 = \frac{A_0}{A_s} E(\varepsilon_i + \varepsilon_r) \quad (3)$$

where ε_i is the measured incident strain signal. The comparison of stresses at both ends of the specimen in Figure 3 indicates that the specimen was in stress equilibrium nearly over the entire duration of loading. Since the conditions of stress equilibrium was satisfied, the engineering stress-strain curve could be calculated with Equations (1) and (2).

Following the same procedure, the compressive stress-strain curves of the wrought and AM 304L stainless steels in different directions were obtained at different strain rates, which are plotted in Figures 4 and 5, respectively.

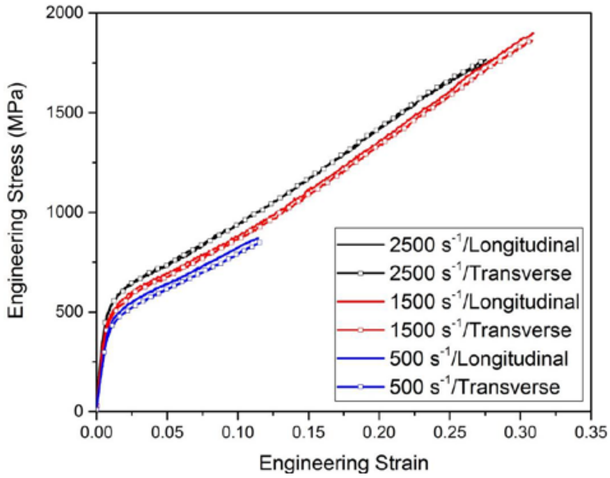

Figure 4. Compression Engineering Stress-Strain Curves (Longitudinal and Transverse Directions) of Wrought 304L SS at Various Strain Rates

Figure 4 shows a nearly isotropic work hardening characteristic in the dynamic compressive stress-strain response for the wrought 304L SS. In addition, the stress-strain curves for the wrought 304L SS show moderate sensitivity to strain rate in both longitudinal and transverse directions. The yield strength and flow stress increase with increasing strain rate.

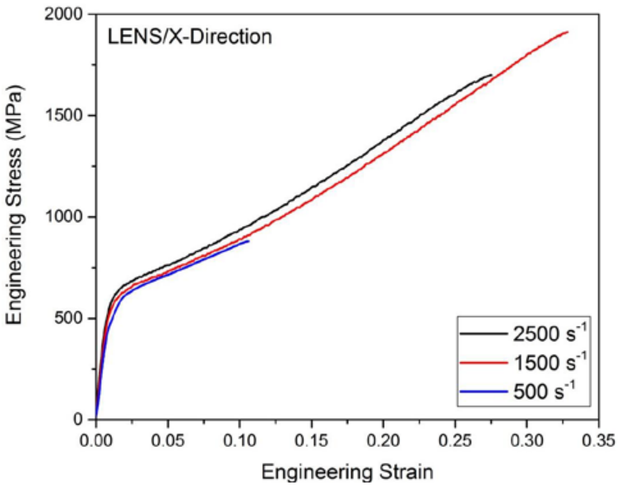

Figure 5. Compression Engineering Stress-Strain Curves (X Direction) of AM 304L SS at Various Strain Rates

As shown in Figure 5, the dynamic compressive response of the AM 304L SS in the X direction had very similar work hardening characteristics to the wrought 304L SS. However, the strain rate dependence seems less significant than the wrought 304L SS.

For comparison purposes, the compressive stress-strain curves of the AM 304L SS are plotted with the wrought 304L SS at each strain rate in Figure 8, Figure 9, and Figure 10, respectively.

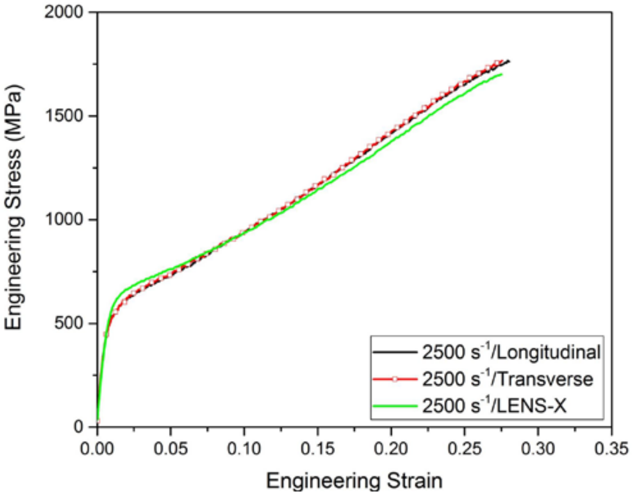

Figure 6. Compression Engineering Stress-Strain Comparison between Wrought and AM 304L SS at 2500 s^{-1}

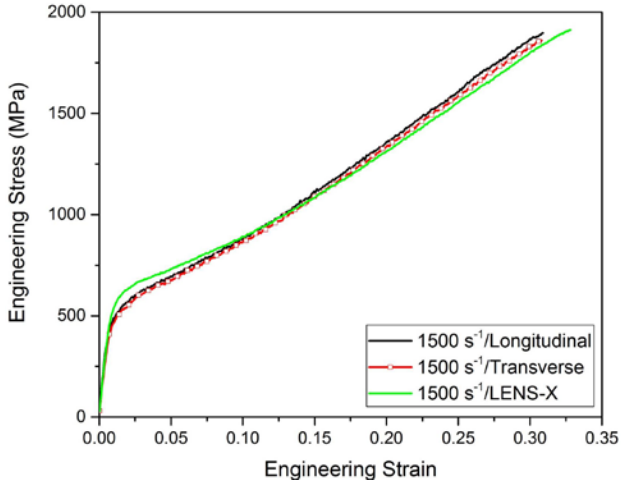

Figure 7. Compression Engineering Stress-Strain Comparison between Wrought and AM 304L SS at 1500 s^{-1}

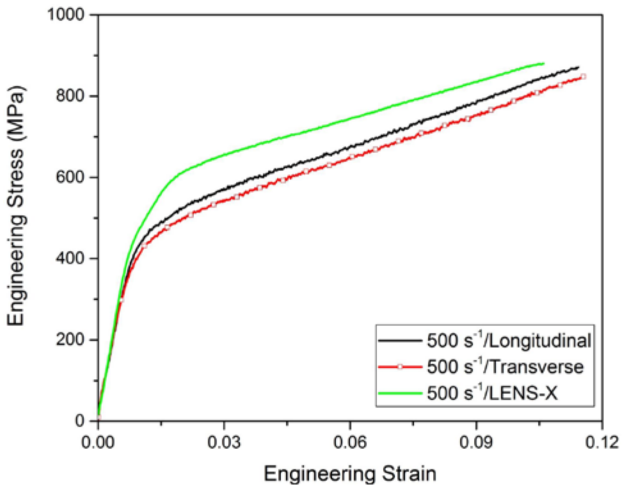

Figure 8. Compression Engineering Stress-Strain Comparison between Wrought and AM 304L SS at 500 s^{-1}

It is apparent that the AM 304L SS in the X direction has higher yield strengths than the wrought 304L SS in both the longitudinal and transverse directions when the strain is smaller than 10%. As strain increases though (above 15%), the stress in the AM 304L SS approaches the wrought 304L SS and eventually becomes lower than the wrought 304L SS.

Although minimal differences are seen when comparing stress-strain curves, a visual difference is apparent in the specimens after testing, as shown in Figure 9.


Figure 9. Wrought (Left) and AM (Right) 304L SS Specimens After Testing

The specimen on the left represents the plastically deformed wrought 304L SS specimen and the AM 304L SS specimen after dynamic loading is shown in the right. It is observed that the wrought 304L SS specimen had a smooth surface with a slight barrel shape on the side due to friction constriction between the specimen and the bar ends. However, the surface of the AM 304L SS specimen shows much rougher ends and side surfaces, which possibly indicates some microstructural changes. The microscopic grain-scale morphology on the AM 304L SS is currently under investigation.

4 Conclusions

A pulse-shaped Kolsky compression bar has been employed to characterize both wrought and AM 304L stainless steels at various high strain rates from 500 s^{-1} to 2500 s^{-1}. The wrought 304L SS was characterized in both longitudinal and transverse directions; whereas the AM 304L SS was characterized in the X direction (the travel direction of laser during AM process) at this moment. The pulse shaper material was carefully designed to obtain nearly constant strain rate in the specimen under dynamic stress equilibrium. The dynamic compressive stress-strain curves were obtained for both wrought and AM 304L stainless steels. Both materials showed very similar work hardening characteristics. However, in comparison to the wrought 304L SS, the yield strength and flow stress for the AM 304L SS were higher at small strains (below 10%) but dropped lower when the strain was larger than 15%, indicating a milder work hardening behaviour in the AM 304L SS along the X direction. Within the dynamic strain rate range investigated in this study, the AM 304L SS also exhibited less strain rate sensitivity than the wrought 304L SS. The surface morphologies for the wrought and AM 304L SS specimens after dynamic tests were significantly different. While still under investigation, speculation can be made that the bands of small grains separated by larger grains is likely responsible for the surface roughness of the AM 304L SS specimens.

5 Acknowledgements

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