Creep Resistance of Additively Manufactured 316 Stainless Steel

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INTRODUCTION

Type 316 austenitic stainless steel (SS) is one of the most widely used structural materials in all types of nuclear reactors including current nuclear power plants and next-generation advanced nuclear reactor concepts, e.g. sodium-cooled fast reactors, molten-salt reactors, and gas-cooled very high temperature reactors. Additive manufacturing (AM) as a disruptive manufacturing technology has opened up unprecedented opportunities for designing next-generation advanced 316 SS with controlled microstructure and enabling smart designs of reactor structural components with complex geometries and design freedom. Previous studies have shown that AM 316 SS has significantly improved yield and tensile strength combined with good ductility than conventionally-made wrought 316 SS at low temperatures [1-3]. The high-temperature mechanical performance of AM 316 SS is yet to be evaluated and fully understood. This paper summaries the recent effort on investigating the creep resistance of AM 316 SS for its core structural applications in the Transformational Challenge Reactor, a gas-cooled microreactor being developed to demonstrate revolutionary technologies including additive manufacturing [4,5].

EXPERIMENTAL

ASTM-standard round bar specimens were fabricated from an additively manufactured 316L SS. The AM 316L SS build was made by a laser powder bed fusion process using a Concept Laser–M2 printer [6]. This two-laser system enables direct one-to-one batch variability within a single build while keeping all other variables constant. Creep specimens were made from round bar sections of Laser 1 mode (Specimen ID, L1XX), and round bar sections of Laser 2 mode (Specimen ID, L2XX), respectively, to evaluate the batch variability. Creep tests were conducted according to the ASTM Standard E139-11, "Standard Test Methods for Conducting Creep, Creep-Rupture, and Stress-Rupture Tests on Metallic Materials" on ATS Series 2300 Lever Arm Creep Testing Systems. Three creep specimens per laser mode were tested at 650°C in air at stress levels of 175, 200, and 225 MPa, respectively. Microstructure of the creep-tested specimens was characterized by optical microscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM), and synchrotron X-ray tomography. A brief summary of the test data is provided below.

RESULTS AND SUMMARY

Figure 1 shows the creep strain as a function of time for the six creep specimens. Specimens made from Laser 1 and Laser 2 modes show remarkably comparable creep behavior. It was also found that no steady-state creep was observed in either of the creep tests. The minimum creep strain rate was reached in the first few hours followed by a continuous increase to failure. The minimum creep rate followed a power law relationship with the applied stress, $\dot{\varepsilon} = A\sigma^n$, with the power exponent of n = 12, as shown in Fig. 2. It implies a low-temperature dislocation creep mechanism.

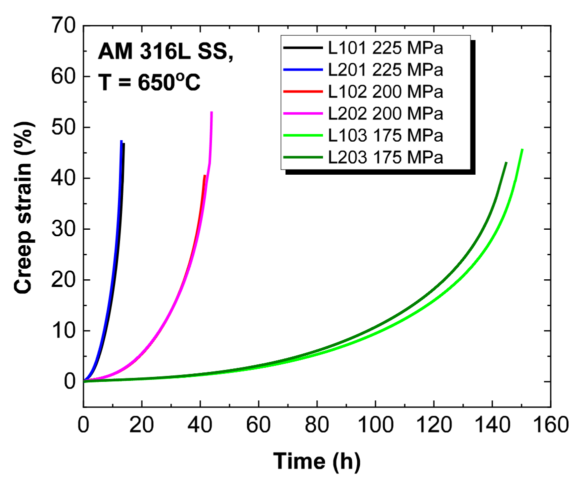

Figure 1. Creep strain as a function of time for AM 316L SS tested at 650°C.

TEM revealed that the initial dislocation cell structure in the as-built AM 316 SS gradually disappeared during creep deformation, and evolved into a high-density dislocation network, as shown in Fig. 3, where the microstructure of the creep-tested (650°C/225 MPa) specimen was examined by taking a TEM specimen in the gauge section away from the fracture surface. Optical microscopy of the gauge section near the fraction surface showed a high density of voids and grain boundary cracks in the creep-tested (650°C/225 MPa) specimen.

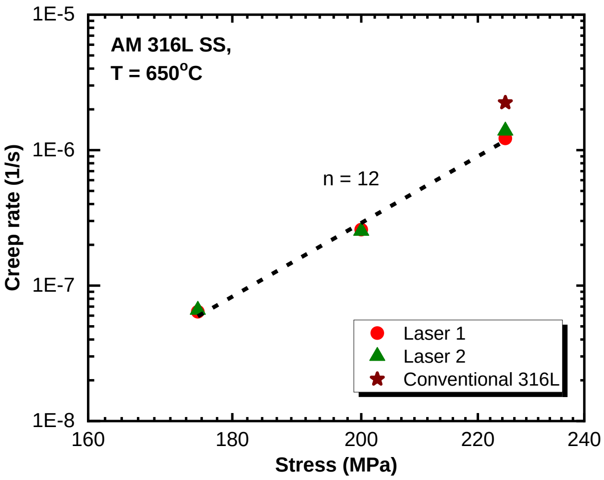

Figure 2. The minimum creep rate vs. applied stress for AM 316L SS tested at 650°C.

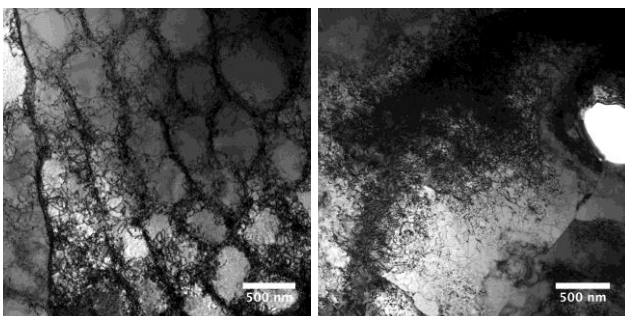

Figure 3. Dislocation cell structure retained from the as-built AM 316LSS (left) and a high-density dislocation network formed after the creep test at 650°C 225 MPa in the AM 316L SS (right).

Creep tests of the AM 316L SS have also been carried out at lower temperatures (e.g. 550°C) and with different heat treatments to better understand its creep behavior and improve its creep resistance through post-built processing.

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