In situ mechanical testing of AM 316L steel –TCR core material[1]

M.N. Gussev* †, T.S. Byun†, T. Lach†, R.R. Dehoff†, K.A. Terrani†

*Oak Ridge National Laboratory, 1 Bethel Valley Road, PO Box 2008, Oak Ridge, TN 37831, gussevmn@ornl.gov
†Oak Ridge National Laboratory

INTRODUCTION

Modern technological approach – Additive manufacturing (AM) allows for the fabrication of complex parts with multiple cavities and channels and with geometry often forbidden for traditional approaches. In the recent few years, the AM techniques have matured enough to fabricate high-quality reactor nuclear components. Currently, a new initiative in the nuclear energy field - the Transformational Challenge Reactor (TCR) [1,2] is being developed to demonstrate a revolutionary approach: deploying nuclear power systems using AM technologies. AM promises a significant reduction in price and deployment time.

However, the properties and performance of the AM material should be certified and confirmed, and any unfavorable changes and features should be mitigated. The present research employs in-situ mechanical testing, assisted by electron-back scatter diffraction (EBSD) analysis to reveal deformation mechanisms and investigate strain hardening and fracture behavior of AM-produced 316L steel – the material of TCR in core components.

DESCRIPTION OF EXPERIMENTAL WORK

The AM 316L steel was produced using the selective laser melting (SLM) technique [3]. To perform testing, SS-J specimen geometry was employed [4]; the specimens were produced by a commercial vendor using an electric discharge system. SEM-EBSD in situ testing was performed using a TESCAN MIRA3 SEM equipped with a miniature tensile frame (Kammrath&Weiss Inc., model MZ.Sb) allowing for mechanical testing of miniature specimens, including irradiated ones. This equipment allowed for step-by-step deformation while measuring material parameters and evaluating strain-induced changes in the structure. SEM-EBSD in situ testing allows for analyzing lattice strains, grain rotation processes, texture evolution, etc. Through in-situ testing, it may be possible to get data for a broad range of stress and strain levels after testing only a single specimen.

EXPERIMENTAL RESULTS

Figure 1 shows tensile curves for an AM-316L steel, tested in- and ex-situ. Small drops in the load mark the test interruptions when EBSD scanning was performed; however, these interruptions had limited influence on the overall tensile curves.

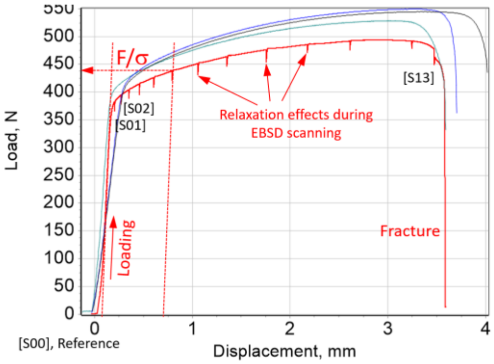

Figure 1. Tensile curves for the ex- (thin, smooth lines) and in-situ (thick red line with relaxation segments) tests. [S00], [S01] – steps of deformation.

One may see good agreement between the ex- and in-situ test results. Also, the AM-material showed higher yield stress (~400 MPa), compared to wrought annealed 316 material (~240 MPa).

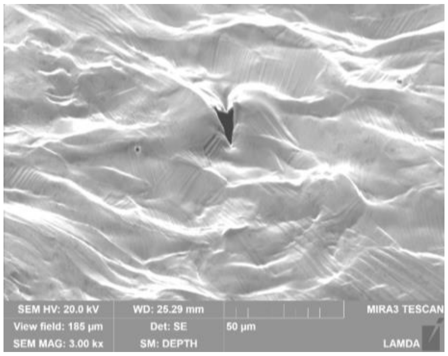

Figure 2. Typical microfracture event (appearance of microcrack) at the surface of the AM 31L steel specimen. Step [S09], which is close to the ultimate stress point, Figure 1.

---

[1] This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doepublic-access-plan

Figure 2 shows a typical surface appearance: strain-induced morphology with multiple slip systems active in most grains and, which is most important, with microcrack (fracture event) observed during tension. Microcracks appear during deformation, tend to grow, and at some point, contribute to the specimen fracture.

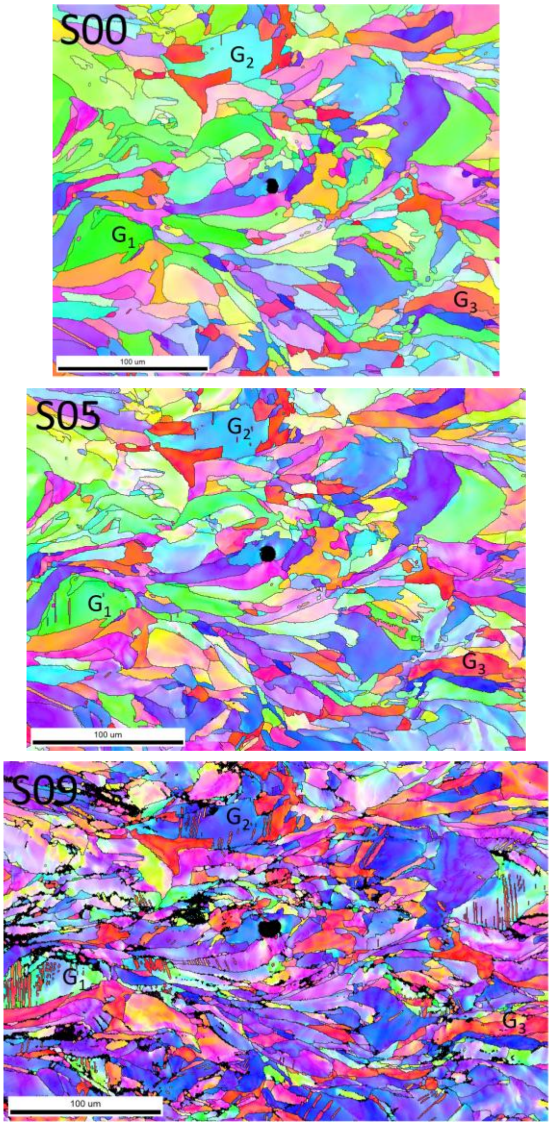

Figure 3. The microstructure of selected region of interest (ROI) at different steps (S00, S05, S09) of in situ test (S00 – reference). G_1-G_3: several grains to illustrate strain-induced phenomena. The IPF maps are colored in the tensile direction.

Figure 3 shows a typical microstructure of the AM-316L steel at different steps of the in situ test. Initial microstructure (Step zero or reference) has elongated grains, often of bend shape, in contrast with conventional wrought 316L steel. However, pre-existing texturing is very weak: grains have pretty random orientation and no color dominates the IPF (inverse pole figure) map.

As the in-situ test starts and progresses (see Step 5, S05 in Figure 3), one may see multiple strain-induced phenomenon in the structure. For instance, grains G_1 and G_2 show a change in the color (orientation), revealing the lattice rotation effect. The lattice rotates towards [001] and [111] orientation, with respect to the tensile direction. These two orientations are stable and such grains (e.g., G_3 in Figure 3) usually retain their orientation through the test.

Additionally, multiple strain-induced twins appear in the structure (see grains G_1 and G_2), starting at a strain level of ~5-7%, much smaller compared to the wrought steel (critical twinning strain ~25% and more).

The full EBSD dataset, not discussed in the Summary, includes also KAM (kernel average misorientation) and GROD (grain reference orientation deviation) data, detailed analysis of lattice rotation, grain size and shape role analysis, twinning phenomena investigation, and analysis of fracture initiation and development.

CONCLUDING REMARKS

The present work offers one of the first insights into the mechanical performance of AM-316L steel via in-situ SEM-EBSD-assisted mechanical testing. Although the mechanical property data produced up to date are very limited, the results show that the performance of the AM materials is not significantly reduced compared to the traditionally processed materials (e.g., wrought 316L steel).

ACKNOWLEDGMENT

This research has been performed as part of the Transformational Challenge Reactor program supported by the US Department of Energy Office of Nuclear Energy

REFERENCES

1. "Transformational Challenge Reactor." Oak Ridge National Laboratory. https://tcr.ornl.gov/
2. K.G. Field et al., “Handbook of advanced manufactured material properties from TCR structure builds at ORNL – FY19,” ORNL/TM-2019/1328 (2019).
3. J. Simpson, J. Haley, C. Cramer, O. Shafer, A. Elliott, W. Peter, L. Love, R. Dehoff, “Considerations for application of additive manufacturing to nuclear reactor core components,” ORNL/TM-2019-1190, Oak Ridge National Laboratory (2019).
4. M.N. Gussev, R.H. Howard, K.A. Terrani, K.G. Field, Sub-size tensile specimen design for in-reactor irradiation and post-irradiation testing, Nuclear Engineering and Design 320 (2017) 298–308.