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Post-irradiation tensile properties of the first and second operational target modules at the Spallation Neutron Source

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ABSTRACT

During neutron production the target module at the Spallation Neutron Source (SNS) is damaged by cavitation-induced erosion and the mechanical properties of the AISI 316L vessel material are altered by high-energy proton and neutron radiation. Recently the first and second operational target modules at the SNS reached the end of their useful lifetime, and disk shaped specimens were sampled from the beam entrance region of both targets. Tensile specimens ranging in dose from 3 to 7 displacements per atom (dpa) were fabricated from the disk specimens using wire electrical discharge machining and tested at room temperature. This paper presents the tensile properties of the irradiated 316L vessel material removed from the first and second operational SNS target modules. Results show an increase in tensile strength and decrease in elongation values similar to previous spallation irradiated 316L results. Abnormally large elongation, 57% total elongation, was observed in a specimen irradiated to 5.4 dpa and considerable scatter was observed in the uniform and total elongation data. One possible explanation for the abnormally large elongations and scatter observed in tensile test results is the so-called *deformation wave* phase transformation-induced plasticity effect. Microscopy characterization revealed the presence of large nonmetallic inclusions rich in Al, S, Ca, O, and Mg on the fracture surface, which may have also contributed to the scatter in the tensile elongation results. While all specimens exhibited radiation-induced hardening and a decrease in ductility, the predominate topographical morphology on all specimen fracture surfaces examined was ductile microvoid coalescence and all specimens experienced appreciable necking prior to fracture. These findings indicate that 316L retains sufficient ductility (10–20% total elongation) and fractures in a ductile manor after irradiation to approximately 6–7 dpa in the mixed proton/neutron radiation environment at the SNS.

1. Introduction

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) is a megawatt class accelerator-based neutron source operated by the United States Department of Energy that generates intense neutron pulses for neutron scattering based research. Neutrons are produced at the SNS by bombarding a target module containing flowing liquid mercury with 1 GeV protons at a frequency of 60 Hz. High-energy proton pulses induce spallation reactions in the mercury target material and liberate high-energy spallation neutrons, which are moderated to useful energies before traveling down beam lines to various neutron-utilizing instruments. Mercury flowing through the target module serves as both the spallation target material and the coolant, taking advantage of its large atomic number and high heat removal capacity. The function of the SNS target module is to introduce the mercury to the target location inside the target core vessel and return the heated mercury to the circulation pump and heat exchanger loop. The SNS target module is composed of AISI 316L stainless steel and consists of an inner mercury target vessel surrounded by a water-cooled shroud. Both the mercury vessel and the shroud are double walled at the proton beam-entrance region where the maximum dose occurs and are cooled by a window flow of mercury and water, respectively. Neutron production at the SNS is dependent on the proper operation of the target module and understanding the changes that occur during service is essential for ensuring reliable operation and neutron production.

In addition to producing moderated neutrons for instruments, the high-energy protons and spallation neutrons also induce changes in the microstructure of the material they interact with, generally referred to as "radiation damage", which alter the

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mechanical properties of the bulk material. Radiation damage to the microstructure is caused by two primary mechanisms: displacement-induced microstructural defects, measured in displacements per atom (dpa), and transmutation gas production. Displacement-induced microstructural damage in metallic materials, such as dislocation loops and defect/void clusters, originate primarily from collisions between neutrons/protons and atoms in the material. Early calculations predicted that in the high-dose locations of the SNS target module, high-energy spallation neutrons would be responsible for approximately 2/3rd of the displacement damage to the SNS target vessel [1]. Transmutation gas production and retention is of particular concern in spallation systems, as the gas production rates for a high-energy (~1 GeV) proton and spallation neutron environment are orders of magnitude higher than typical fission and fusion irradiation environments. Depending on the alloy constituents, helium production rates of typical structural alloys in fission and fusion environments are approximately 0.1–50 and 10 appm He/dpa, respectively, while He production rates in typical spallation systems range between 50 and 160 appm He/dpa [2,3]. Previous work indicates that increased He production and retention in 316L are partially responsible for the accelerated loss of ductility observed in specimens exposed to a spallation radiation environment relative to results from specimens irradiated in fission environments [4,5].

Radiation-induced changes in the microstructure of 316L alter the bulk mechanical properties, which typically manifest as an increase in tensile strength, reduction in ductility, and decrease in fracture toughness. Radiation-induced changes in mechanical properties of austenitic stainless steels exposed to spallation environments have been well studied over the past decade [4–10] and several conclusions have been established:

1. Significant hardening, manifested as an increase in yield strength, occurs in austenitic steels after only a few tenths of a dpa [4,5,7]; the yield strength of 316L has been shown to double after approximately 1 dpa [8].
2. Elongation values decrease with increasing dose, but 316LN, a nitrogen enriched version of 316L, has been shown to retain uniform and total elongation values as much as 6% and 12%, respectively, after 11 dpa in a spallation environment [8].
3. Elongation values have also been shown to sensitive to test temperature, with as much as a 8–36% decrease in ductility when temperature is increased from 20 to 164 °C [5].
4. Several observations suggest that, while loss of ductility appears to be accelerated in a spallation environment relative to a fission environment after approximately 1 dpa [5,8], the loss of ductility appears to saturate around 10 dpa [10], after which elongation values decreased little with increasing dose.
5. Fracture toughness values (K_{JQ}) for 316L have been shown to decrease below 120 MPa $\sqrt{m}$ after irradiation to ~4.5 dpa in a spallation environment, but the decrease appears to saturate after approximately 6 dpa to values around 60–80 MPa $\sqrt{m}$ [4].

It should be mentioned that while austenitic steels such as 316L undergo a loss of ductility and reduction in fracture toughness with increasing dpa dose, the austenitic family of stainless steel alloys has been proven to be far more resistant to radiation-induced changes in mechanical properties relative to other viable structural materials. For example, work by Farrell and Byun showed that after irradiation in a spallation environment at the Los Alamos Neutron Science Center (LANSCE) to approximately 2 dpa the uniform elongation values for ferritic/martensitic alloys 9Cr–2WVTa and Modified 9Cr–1Mo decreased to 0.8% and 0.5%, respectively, while a European 316LN variant retained 6.0% uniform elongation after irradiation to ~11 dpa in the same environment [8]. Also, austenitic steels do not experience a transition from a ductile to brittle fracture mode with decreasing temperature, which occurs in ferritic/martensitic steels at a characteristic temperature, called the ductile to brittle transition temperature (DBTT). The ability to retain sufficient ductility and fracture toughness during operation in a spallation radiation environment are two of the primary reasons austenitic stainless steel 316L has been used to fabricate the target modules for the SNS at ORNL [11] and the Japanese Spallation Neutron Source (JSNS) [12], also called the Materials and Life Science Experimental Facility (MLF), at the Japan Proton Accelerator Research Complex (J-PARC) [13].

The SNS target module is a necessary component for neutron production and reliable operation is critical for maintaining neutron availability at the SNS. Understanding the rate of strengthening and loss of ductility that occurs in the SNS target module during operation is necessary for establishing prudent administrative dose limits for periodic replacement of the target module and establishing a reliable operational schedule for the SNS. Another issue unique to pulsed liquid–metal spallation targets is cavitation-induced erosion; a phenomenon where the inner surface of the target module is eroded by collapsing mercury bubbles initiated and grown by beam-induced cavitation [14–17]. A Post Irradiation Examination (PIE) program was implemented at the SNS [18] to: (1) characterize the changes in mechanical properties of the target material as a function of dose, (2) characterize the extent of cavitation-induced erosion to the target vessel interior surface, and (3) evaluate any failures or issues experienced with target modules during operation. Early PIE examinations of Targets 1 and 2 revealed significant cavitation-induced erosion had occurred to the mercury target vessel interior surfaces during operation [19], and confirmed suspicions that cavitation could significantly erode target containers in pulsed high-power liquid metal spallation neutron systems [16]. At the time of this publication, disk-shaped specimens with a 60.3 mm (2 3/8 in) diameter have been removed from the proton beam entrance region of the mercury target vessel and water-cooled shroud of SNS Targets 1–8. Presented here are the tensile testing results for specimens produced from material of the first and second operational SNS target modules, referred to as Target 1 and Target 2, respectively.

2. Experimental procedure

2.1. Specimen production

Curved disk-shaped specimens were removed from SNS target modules using a sampling device designed to hold the target and cut samples from a variety of locations along the beam entrance region of the target module using a carbide-tipped annular cutter [18,19]. Four disks were chosen from both Targets 1 and 2 for more detailed examination and testing: Disks 1, 5, 6, and 7, identified in Fig. 1. The disks were cleaned using a series of ultrasonic baths with cleaning solutions to remove debris and deposits that adhered to the target module interior surface and swarf from the cutting process [20]; the before and after cleaning pictures for Disk 6 removed from Target 2 are shown in Fig. 2.

A variety of specimens were machined from the disk specimens removed from Targets 1 and 2 to accomplish the series of characterizations, including: Rockwell hardness, Vickers microhardness, tensile testing, optical and scanning electron microscopy. The machining process was initiated by outlining machining maps for each disk specimen, as shown in Fig. 3, where specimen type and approximate location were superimposed on an image of a cleaned disk. The approximated specimen locations on the disk images were used to produce digital machining maps, which were utilized by an electrical-discharge machining (EDM) machine to direct the wire-cutting pathways and cut specimens from the disks. Due to