Current Status of HFIR Irradiation Testing Supporting the Transformational Challenge Reactor

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dx.doi.org/10.13182/T124-35040

INTRODUCTION

The Transformational Challenge Reactor (TCR) program aims to leverage advances in materials, computation, and manufacturing to deliver new enabling technologies for efficient and cost-effective deployment of advanced reactors. Materials and components designed and derived from TCR's agile development cycles via advanced manufacturing need to accompany high quality properties data prior to and after irradiation. Accelerated irradiation testing in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) is part of this process, allowing data on advanced materials to be quickly acquired [1, 2]. Initial irradiation testing campaigns on additively manufactured (AM) silicon carbide (SiC), AM 316L stainless steel (SS), and gas-solid-reaction-derived yttrium hydride (YH_x) have been performed while additional irradiation campaigns on these materials as well as AM Inconel 718 is ongoing.. These materials—either novel or fabricated using advanced manufacturing routes—are intended for use in the advanced reactor cores.

Irradiation testing of AM SiC has been completed [3]. Post-irradiation examinations (PIEs) of AM 316L SS [4] and YH_x are ongoing, and a second HFIR irradiation campaign on these materials is being performed. This summary describes the PIE and current status of the TCR irradiation testing performed on AM 316L SS and YH_x materials.

PIE STATUS

316L SS Irradiation Testing

Some structural components of the TCR fuel assembly are intended to be made of AM 316L SS. The irradiation testing of this material consists of six capsules, which allow irradiation of tensile specimens at either 300°C or 600°C and doses of 0.2, 2, and 8 dpa. Table I presents the irradiation test matrix.

TABLE I. 316L Irradiation Test Matrix

Capsule ID	Irradiation temperature	Dose (dpa)	Material
GTCR01	300°C	0.2	Wrought 316L and
GTCR02		2	3D-printed 316L
GTCR03		8	(as-printed, printed
GTCR04	600°C	0.2	+650°C, or
GTCR05		2	1,050°C heat
GTCR06		8	treatment)

Capsules GTCR01, 02, 04, and 05 completed irradiation and were disassembled at the Irradiated Materials Examination and Testing (IMET) facility at ORNL. The passive thermometry (TM) was shipped to the Low Activation Materials Development and Analysis (LAMDA) laboratory to determine the average irradiation temperature of each capsule by using the dilatometry method [5]. The TM results are presented in Table II and in general are in agreement with the target irradiation temperatures. Hot cell tensile testing at both room temperature and the irradiation temperatures was performed on 32 unirradiated and irradiated specimens made of wrought or AM 316L SS. Fig. 1 [4] presents the engineering stress vs. engineering strain curves for these materials tested at room temperature. All tests showed reasonable ductility. Generally, materials that were shown to have higher pre-irradiation strength showed a lower increase in strength after irradiation. Likewise, materials with lower pre-irradiation strength retain better ductility after irradiation. PIE also includes microscopy and in-situ deformation testing using scanning electron microscopy (SEM).

TABLE II. TM results for 4 GTCR capsules

Capsule ID	Irradiation temperature	Dose (dpa)	Specimen temperature (measured)
GTCR01	300°C	0.2	250 ± 4°C
GTCR02		2	376 ± 25°C
GTCR04	600°C	0.2	673 ± 45°C
GTCR05		2	600 ± 11°C

Twenty additional tensile tests at temperatures around or below the irradiation temperatures are planned for the 0.2 and 2 dpa specimens. The higher-dose capsules, GTCR04 and GTCR06, will complete irradiation in March 2021. PIE on those capsules will include TM dilatometry, tensile testing, microscopy, and SEM.

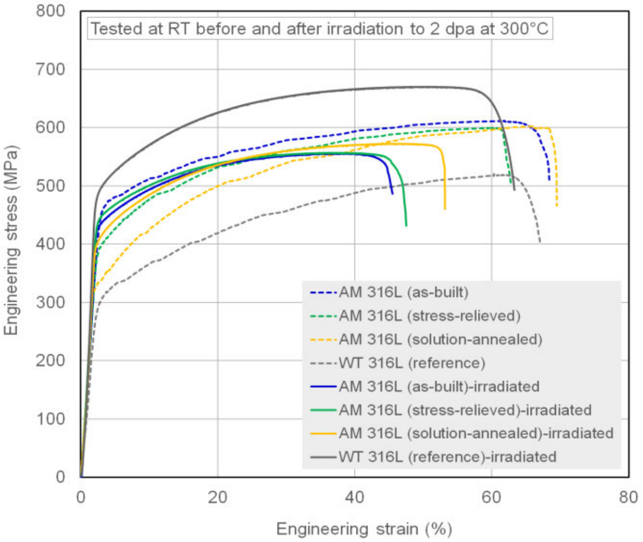

Fig. 1. Room temperature (RT) engineering stress vs. engineering stain curves for the different AM and wrought (WT) 316L materials, before and after irradiation to 2 dpa at 300°C.

YH_x Irradiation Testing

YH_x was selected as the moderator material in the TCR core due to its high hydrogen atom density and exceptional thermal stability [6]. To acquire data on this material's performance and properties under irradiation, 12 capsules that accommodated the YH_x disk specimens were irradiated in HFIR. The corresponding irradiation test matrix presented in Table III covers two irradiation temperatures, three doses, and two specimen hydrogen contents.

TABLE III. YH Irradiation Test Matrix

Capsule ID	Irradiation Temperature	Dose (dpa)	Material
YHXT01	600°C	0.1	$YH_{1.72}$
YHXT02		1	
YHXT13		2	
YHXT04	900°C	0.1	
YHXT05		1	
YHXT14		2	
YHXT07	600°C	0.1	$YH_{1.85}$
YHXT08		1	
YHXT09		2	
YHXT10	900°C	0.1	
YHXT11		1	
YHXT12		2	

All capsules completed irradiation and were disassembled in IMET. The TMs and specimens were shipped to LAMDA for PIE. The average irradiation temperature for each capsule will be determined using the dilatometry method on the TMs. PIE on the YH_x includes thermophysical and thermomechanical properties measurements to determine the swelling, density, thermal diffusivity, specific heat capacity, Vickers hardness, and flexural strength of the specimens. The PIE results are expected during the summer of 2021. The data collected will be compared with pre-irradiation data to assess the effects of irradiation on YH_x materials.

SECOND IRRADIATION TESTING CAMPAIGN

316L SS and Inconel 718 Irradiation Testing

As part of the second irradiation testing campaign, tensile specimens from AM 316L SS and Inconel 718 were fabricated. Every individual specimen in these capsules is accompanied by a set of spatially selective digital data collected in situ during the AM process. This data is stored in the TCR Digital Platform and will be used in conjunction with PIE test results to correlate in situ manufacturing and ex situ testing data during and after service. The goal of this irradiation testing is to establish a correlation between the material properties post-irradiation and the data collected during fabrication.

Tensile specimens were cut via electron-discharge machining (EDM) from the center, surface, and intermediate layer of the AM 316L plates. Fig. 2 shows a set of specimens after EDM. Wrought and AM Inconel 718 specimens were also fabricated. Three blocks from the same AM Inconel 718 plate were heat-treated under different conditions, and specimens from each block were cut via EDM.

Eight capsules will accommodate the 316L and Inconel 718 specimens for irradiation at two temperatures and two doses. Table IV presents the corresponding irradiation test matrix. The capsules will be inserted in HFIR during the spring of 2021. PIE will include tensile testing at room temperature and at the irradiation temperature.

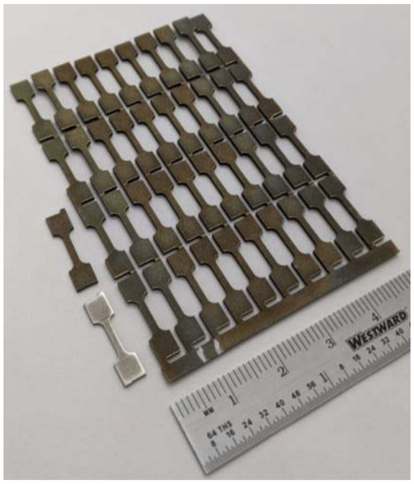

Fig. 2. 316L tensile specimens during the machining process.

TABLE IV. 316L Irradiation Test Matrix

Capsule ID	Irradiation temperature	Dose (dpa)	Material
GTCR07	300°C	2	AM 316L
GTCR08	600°C	2	
GTCR09	300°C	10	
GTCR10	600°C	10	
GTCR11	300°C	2	AM 316L + Alloy
GTCR12	600°C	2	718 (wrought +
GTCR13	300°C	10	AM)
GTCR14	600°C	10	

YHx Irradiation Testing

To mimic the real application environment of this moderator material, additional irradiation testing of YH_x specimens will be performed with the specimens in contact with SiC and 316L SS. The goal of this irradiation testing is to evaluate the chemical compatibility of the materials under irradiation. Additional data will also be collected on YH_x specimens, such as dimensional-change measurements, fracture testing, and hydrogen retention in SiC and SS.

The capsule irradiation design is shown in Fig. 3. Each capsule accommodates 16 YH_x disk specimens and 16 disk specimens made of either SiC or 316L SS. The YH_x specimens are pressed against disk specimens made of SiC or SS. Both AM and chemical-vapor-deposited SiC will be inserted in the capsules, as well as AM and wrought SS specimens. A sealed holder contains the specimens and minimizes the potential hydrogen release from the YH_x specimens to the external capsule housing and potentially to the HFIR coolant. TMs are placed against the specimens, and retainer springs press the specimen assemblies to the holder wall.

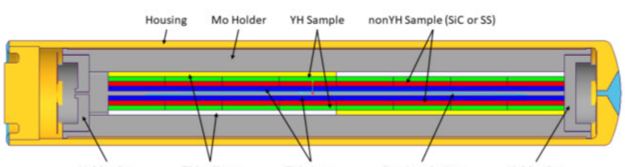

Fig. 3. Capsule design for irradiation testing of YHx and compatibility with SiC or 316L SS.

Three capsules are planned to be built for this irradiation testing, with irradiation conditions at two temperatures and one dose. Table V shows the corresponding test matrix. Thermal analyses were performed to determine the capsule parameters that could enable the desired average specimen irradiation temperatures. Fig. 4 shows an example of the thermal analysis results.

The capsules are intended to be inserted in HFIR for one cycle during the summer of 2021, and PIE is expected to start during the fall of 2021.

TABLE V. YH Irradiation Test Matrix

Capsule ID	Irradiation Temperature	Dose (dpa)	Specimen Material
YHXS01	600°C	2	$YH_{1.85}$ + SiC
YHXS02	900°C	2	$YH_{1.85}$ + SiC
YHXS03	600°C	2	$YH_{1.85}$ + SS

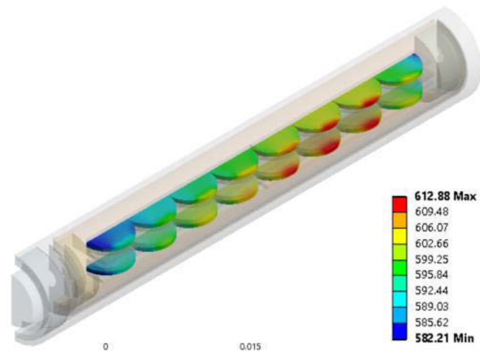

Fig. 4. Thermal analysis results (temperatures in °C) for YHXS03: YH_x specimen temperatures.

CONCLUSIONS

This summary presents the irradiation testing being performed on AM 316L and YH_x specimens to support the development and delivery of high readiness level technologies towards enabling deployment of advanced reactors under the TCR program. Most of the irradiation capsules from the first irradiation campaign have completed irradiation and have begun PIE. The PIE results collected to date as well as future PIE are reported. Additionally, the status of the second irradiation campaign with the goal of collecting additional data on 316L and YH_x materials is reported. The material properties data collected from these irradiation campaigns are critical for the design and licensing of AM materials intended for application in advanced reactor cores.

ACKNOWLEDGMENT

The TCR program is supported by the US Department of Energy's Office of Nuclear Energy.

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