ORNL/TM-2024/3332

Fabrication of a Liner Assembly for the MARVEL Microreactor

Frederick List
Ryan Dehoff
Keith Carver
Chase Joslin
Brian Jordan
et al.

April 2024

M3CR-22OR0405011

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2024/3332

Advanced Materials and Manufacturing Technologies Program
US Department of Energy Office of Nuclear Energy

FABRICATION OF A LINER ASSEMBLY FOR THE MARVEL MICROREACTOR

Frederick List
Ryan Dehoff
Keith Carver
Chase Joslin
Brian Jordan
Ryan Duncan
J. R. Matheson
Tim No

April 2024

DOE Milestone M3CR-22OR0405011

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AM	additive manufacturing
CNC	computer numerical control
DED	directed energy deposition
IHX	intermediate heat exchanger
LPBF	laser powder bed fusion
MARVEL	Microreactor Applications Research Validation and Evaluation
MDF	Manufacturing Demonstration Facility
ORNL	Oak Ridge National Laboratory
SS	stainless steel

ACKNOWLEDGMENTS

This research was sponsored by the US Department of Energy Office of Nuclear Energy Advanced Materials and Manufacturing Technologies Program under contract DE-AC05-00OR22725 with UT-Battelle LLC. The authors gratefully acknowledge the efforts and contributions of Thomas Butcher.

ABSTRACT

A liner assembly for an intermediate heat exchanger (IHX) within the Microreactor Applications Research Validation and Evaluation (MARVEL) microreactor at Idaho National Laboratory has been fabricated using laser-based additive manufacturing (AM). The liner design includes challenging features such as long thin walls, overhangs, and tight geometric tolerances. Two versions of the liner assembly, one full-length and the other shortened, were printed from several materials (316L stainless steel [SS], Inconel 625, and Inconel 718) using four powder-based laser printers (BeAM Modulo 400 directed energy deposition [DED], EOS 290M laser powder bed fusion [LPBF], General Electric [GE] Concept Laser M2 LPBF, and GE Concept Laser Xline 2000R LPBF) located at the Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory (ORNL). Dimensional accuracy, print time, and powder utilization have been evaluated to help assess the feasibility of these advanced manufacturing approaches to liner fabrication. Based on this assessment, a potentially cost-effective pathway for fabrication has been proposed.

1. BACKGROUND

A key thrust of the Advanced Materials and Manufacturing Technologies Program is manufacturing and demonstrating components for use in the deployment of nuclear energy. Additive manufacturing offers a sometimes-unique opportunity to tailor the designs of components to perform in the harsh irradiation environments (high temperatures, pressures and/or corrosivity) associated with advanced nuclear reactors. This report describes an effort to design and print an AM liner assembly for an IHX within the MARVEL 100 kW fission microreactor that is under development at Idaho National Laboratory. Figure 1 shows an illustration of the approximately 1–ton microreactor. The microreactor employs natural circulation cooling using liquid sodium–potassium at an operating temperature of 500-550°C. Each of the four IHXs in the microreactor can be equipped with a liner assembly that consists of two parts—a liner and a downcomer (see Figure 2). The entire liner assembly is fully immersed in liquid metal during the operation of the microreactor and is designed to be simply replaced if needed during routine reactor maintenance.

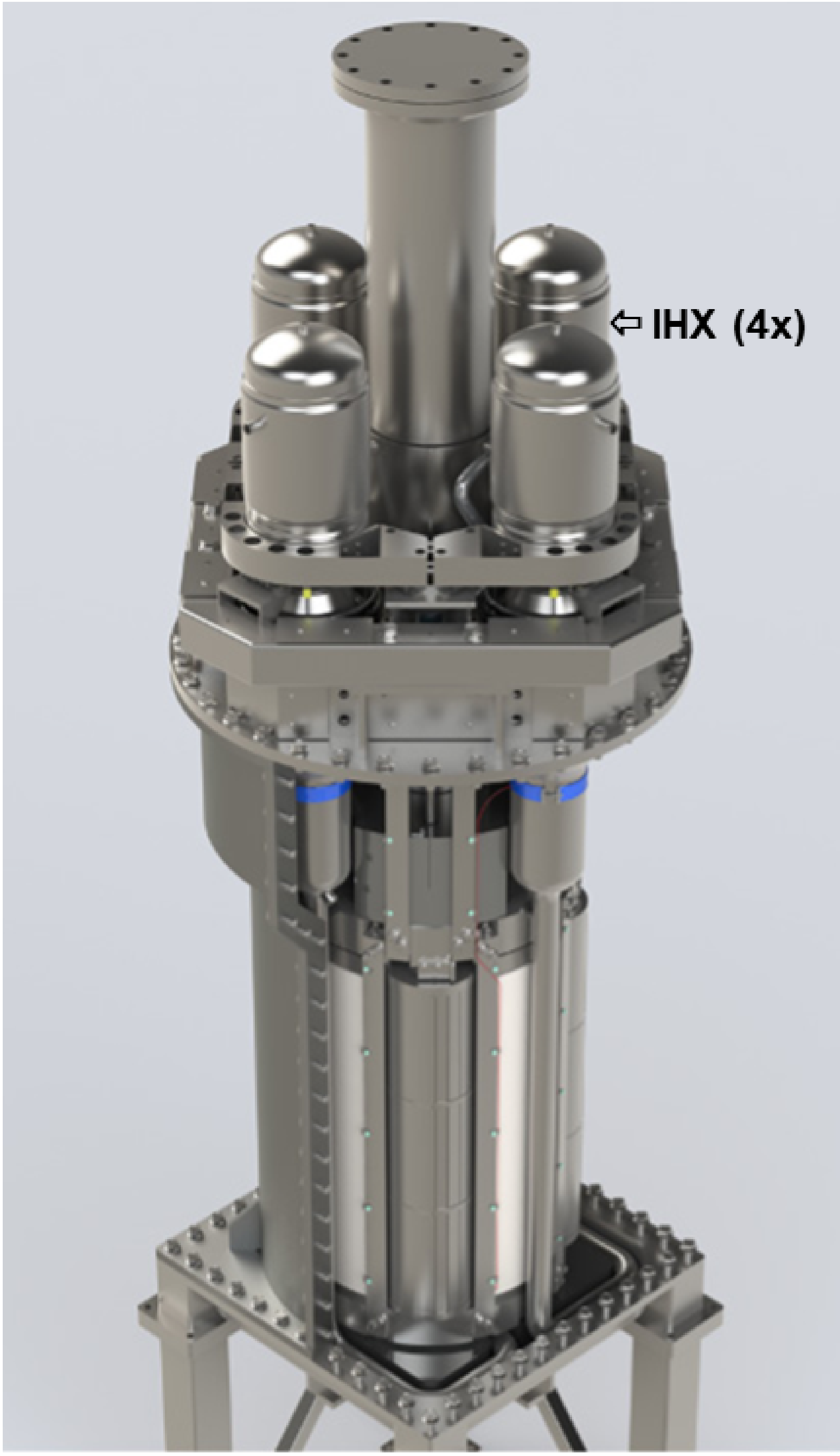

Figure 1: Illustration of the MARVEL microreactor at Idaho National Laboratory[1].

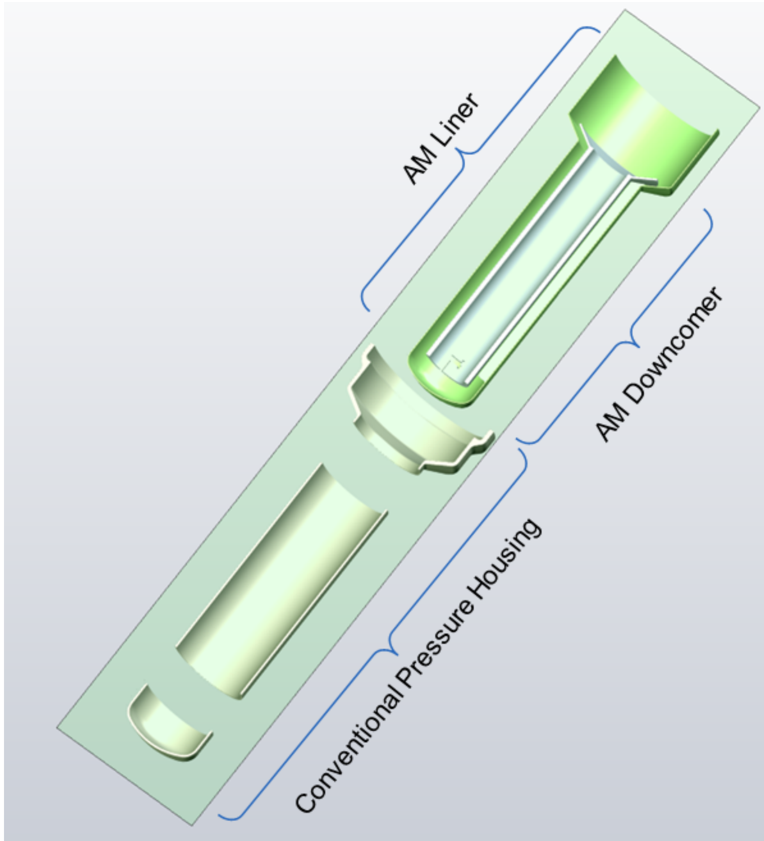

Figure 2: Exploded view of the liner assembly within the IHX. The liner and downcomer are designed to be simply and individually replaceable; the housing is not simply replaceable.

The principal goal of this effort is to print a full-scale liner assembly that meets both the requirements of the design and the capabilities of the available fabrication equipment. The design specifies thin walls (~2 mm) over long distances (~620 mm overall length) and targets small clearances between the housing and liner (~0.15–0.05 mm) to facilitate heat transfer from the reactor core via the liquid metal coolant. The design also includes a significant low-angle conical overhang. The approach used to meet these challenging design requirements was to select several AM printers available at the MDF of ORNL, print demonstration components of the liner assembly (either full-height or shortened), and evaluate the components. Although the final design calls for 316L SS, demonstration components were printed of the resident materials within the printers. Table 1 summarizes some of the features of the printers used for this effort.

Table 1. Some features of the printers used to print liner components. The approximate elemental composition (wt.%) of each material is listed in the right columns.

Printer	Type	Maximum capacity (x×y×z) (mm)	Material	Ni	Fe	Cr	Mo	Nb+Ta	Co	Mn
EOS 290M	LPBF	250×250×325	Inconel 625	58	5	22	9	4	1	—
GE Concept Laser M2	LPBF	250×250×350	316L SS	12	66	17	2	—	—	2
BeAM Modulo 400	DED	400×400×650	316L SS	12	66	17	2	—	—	2
GE Concept Xline 2000R	LPBF	800×400×500	Inconel 718	53	18	18	3	5	1	—

2. RESULTS

The first component to be printed was a shortened downcomer, approximately one-third of the full height. An EOS 290M LPBF printer was used with Inconel 625 powder. Figure 3 shows the outcome of the printing. Although it was not undertaken, post machining of the shortened downcomer to meet the requirements of the design would likely be limited and only involve removing of the support material shown in Figure 3b.

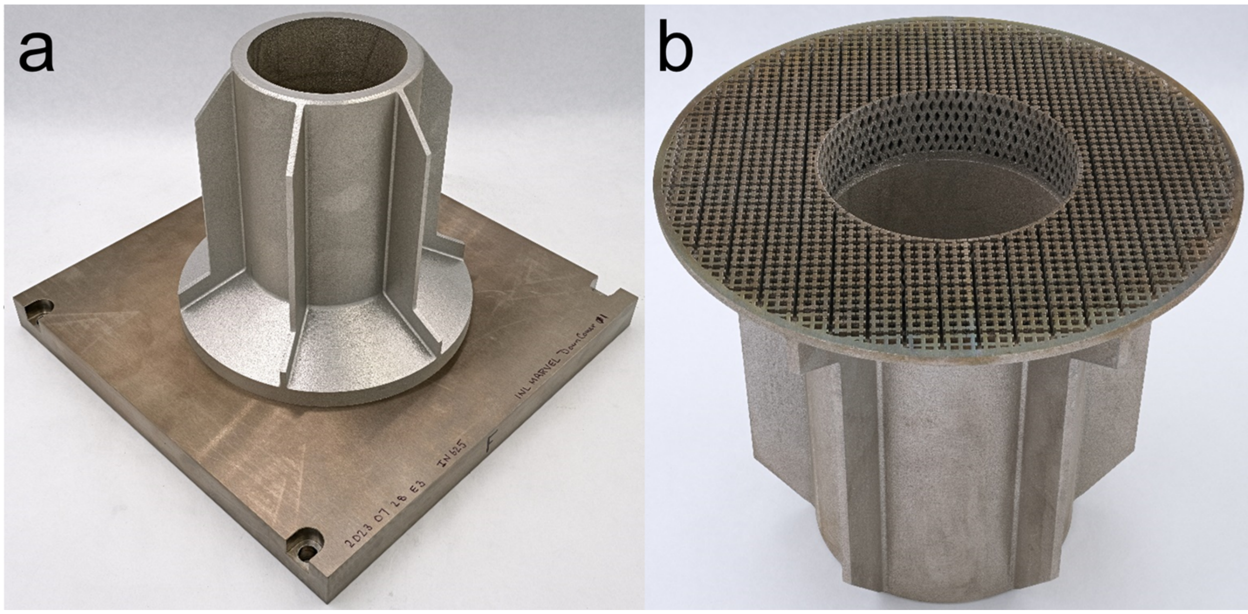

Figure 3: Shortened downcomer of Inconel 625 with a build time of approximately 53 h. Image (a) shows the downcomer attached to the substrate immediately after printing. Image (b) shows the “waffle” support material remaining on the downcomer after removal from the substrate using wire electrical discharge machining (EDM).

Next to be printed was a shortened liner, again approximately one-third of the full height. This printing was accomplished using a GE Concept Laser M2 LPBF printer and 316L SS powder. Additional material (3 mm) was added to the inner and outer walls of the printed liner to facilitate subsequent machining. Figure 4 shows the shortened liner after printing and during machining. The tool used for machining this liner was a five-axis DMG Mori 60 Evo computer numerical control (CNC) machine.

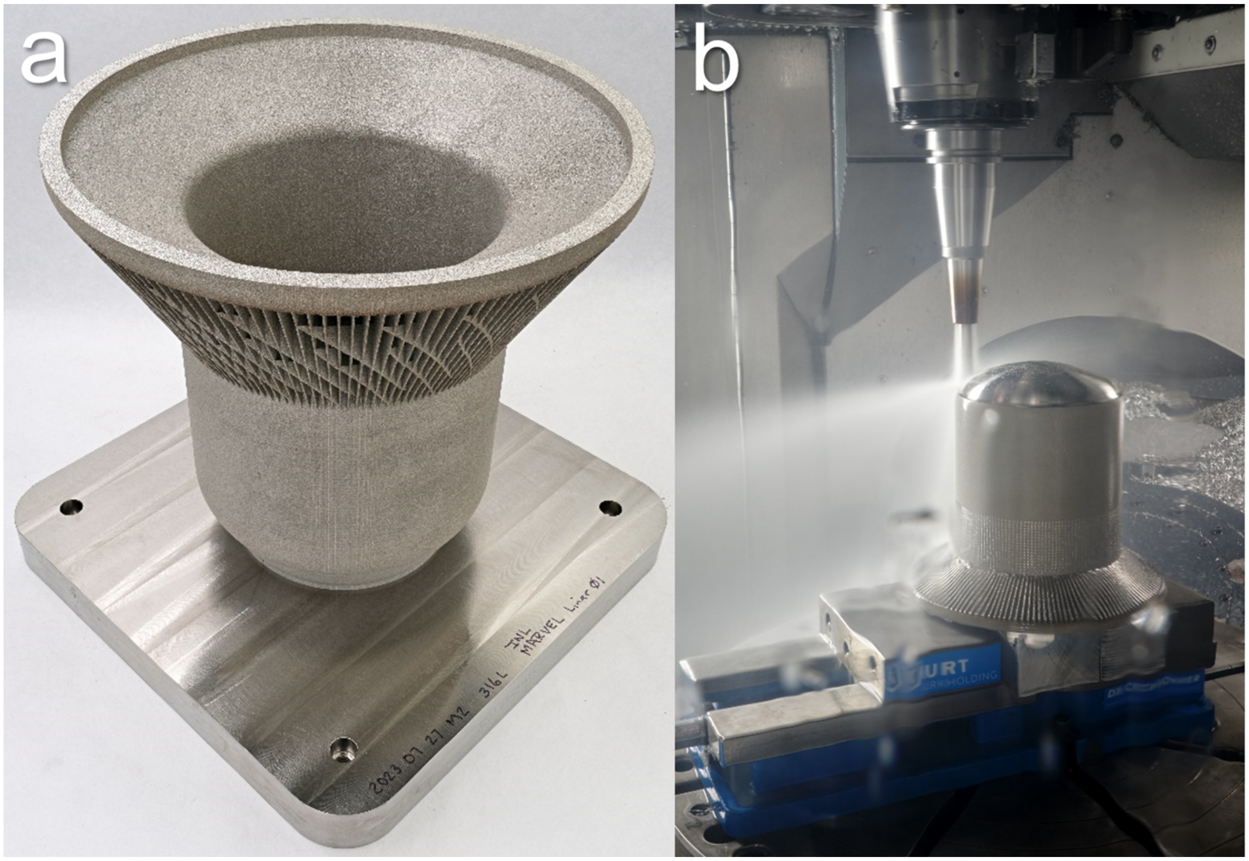

Figure 4: Shortened and thickened LPBF liner of 316L SS with a build time of 109.5 h. Image (a) shows the liner attached to the substrate immediately after printing. Image (b) shows the liner during post-print machining with a machining time of 9.5 h.

To assess the dimensional quality of the shortened LPBF liner after machining, a GOM ATOS Q 3D blue light scanner was used. Some of the results from this scanner are shown in Figure 5. Deviations of the outer surface of the liner from the model are excellent and consistently less than ±0.30 mm.

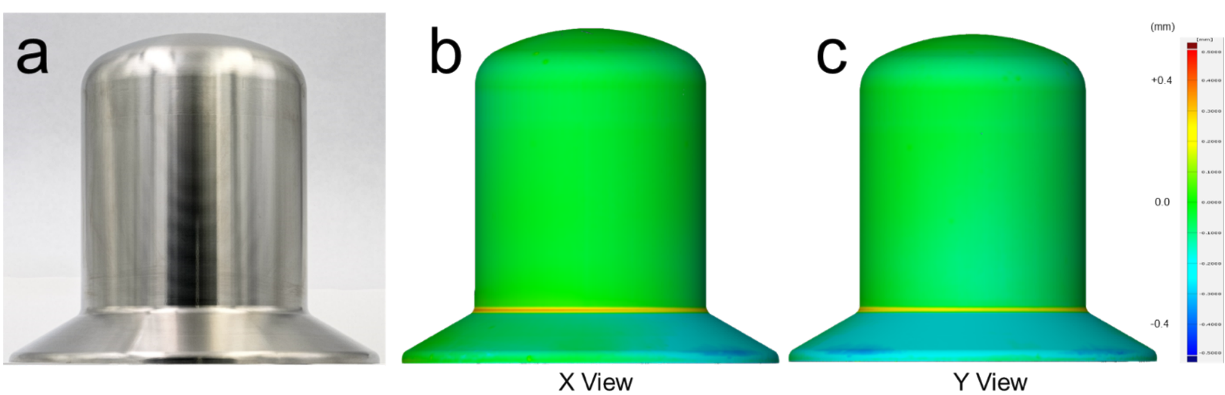

Figure 5: Shortened LPBF liner of 316L SS after machining. (a) Optical image of the liner, (b) color map of the deviation of the liner from the model viewed along the *x*-axis, and (c) color map of the deviation of the liner from the model viewed along the *y*-axis.

To verify the fit of the shortened liner/downcomer assembly, the shortened downcomer was inserted into the shortened liner without interference or excessive play (see Figure 6).

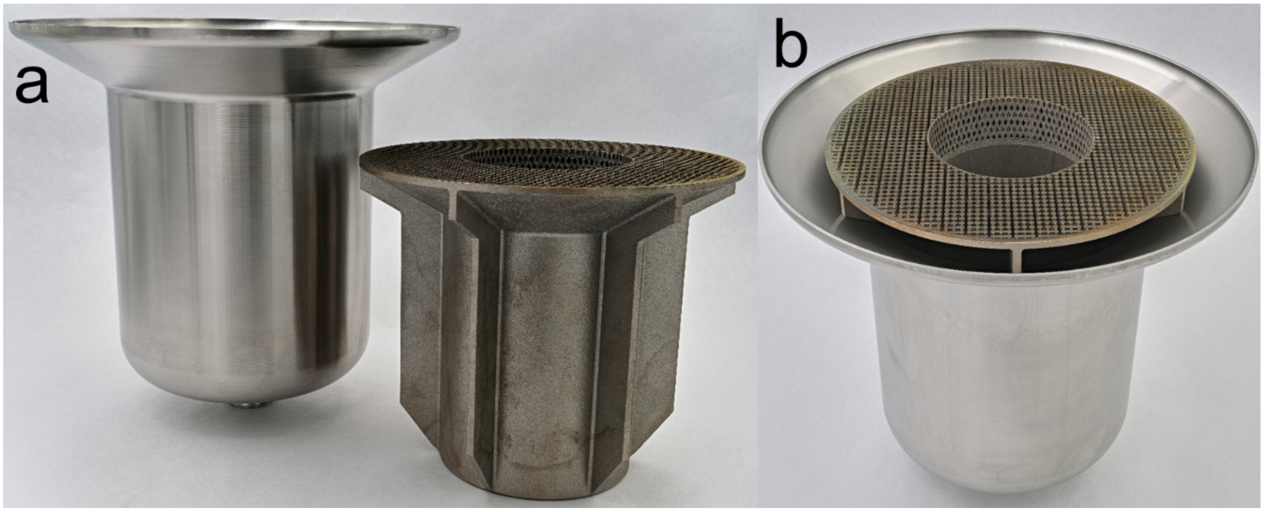

Figure 6: LPBF shortened liner and downcomer (a) before and (b) after assembly.

The maximum capacities in the vertical direction for the EOS 290M and Concept M2 LPBF printers are 325 and 350 mm, respectively. Fabrication of full-height liners and downcomers (overall length ~620 mm) with these printers would require joining two or perhaps three printed sections. For the BeAM Modulo 400 DED printer, the maximum vertical capacity is 650 mm. This capacity would seem to offer the opportunity to print the full-height liner in one piece. However, because five-axis motion (tilt of the principal rotation axis from vertical) is required to accommodate the overhung design, the actual vertical capacity of the BeAM DED printer for the liner is similar to those of the EOS 290M and Concept Laser M2 LPBF printers.

Figure 7 shows the printing of a shortened liner onto the end of a 0.75 in. diameter stub with the BeAM DED printer. The vertical rotation axis depicted in Figure 7 must be tilted approximately 45° when the conical portion of the liner is printed. This obligatory tilt significantly reduces the potential capacity of the printer in the vertical direction.

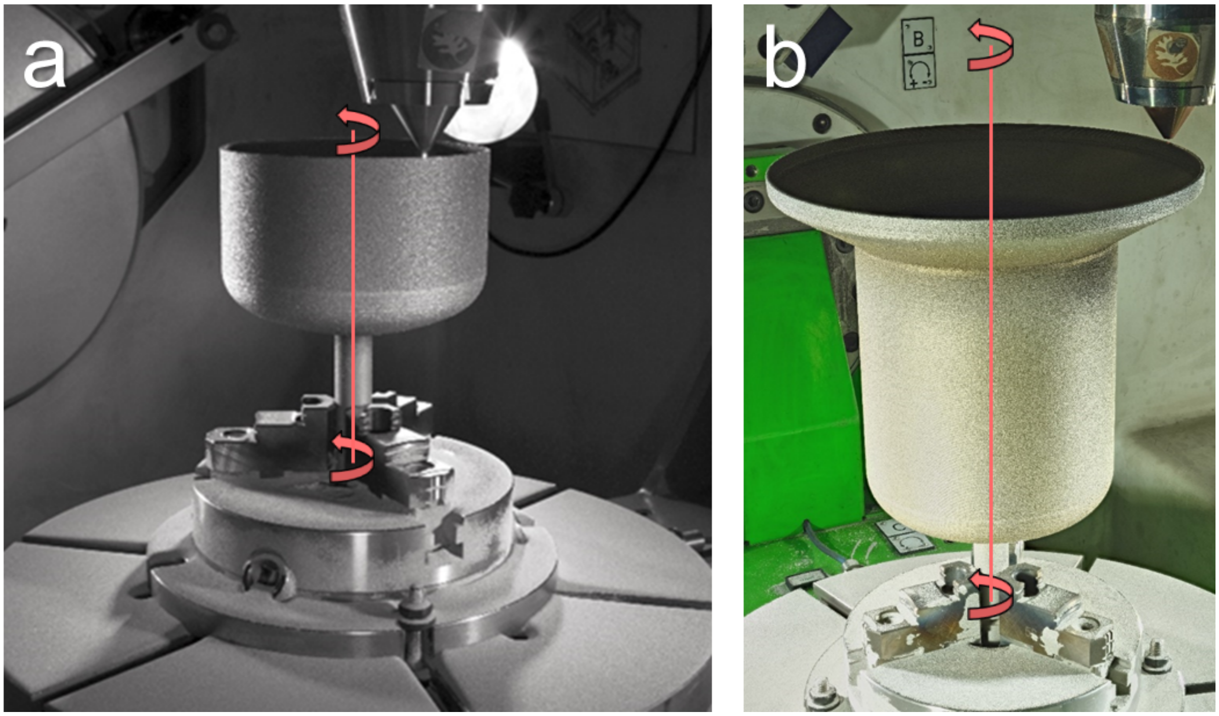

Figure 7: DED shortened liner. (a) Liner in the printer midway into the build and (b) liner in the printer at the completion of the build with a build time of 27 h and powder utilization equal to 17%. The red graphical line depicts the vertical rotation axis.

The dimensional quality of the as-printed, shortened DED liner was assessed with the GOM blue light scanner; some results are shown in Figure 8. Deviations of the outer surface of the as-printed DED liner from the model are generally greater than those for the machined LPBF liner (see Figure 5) but are consistently less than ±0.75 mm. Because the average wall thickness of the as-printed DED liner was only approximately 2.4 mm, post-machining presented challenges and was not performed.

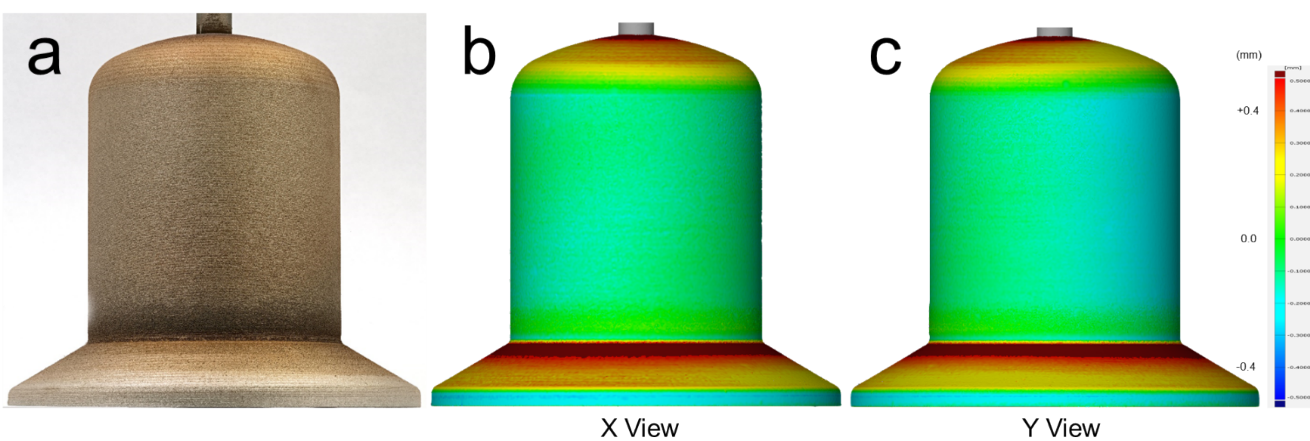

Figure 8: Shortened as-printed DED liner of 316L SS. (a) Optical image of the liner, (b) color map of the deviation of the liner from the model viewed along the *x*-axis, and (c) color map of the deviation of the liner from the model viewed along the *y*-axis.

Following the efforts to print shortened liner components, an attempt to print a full-height liner was undertaken using Inconel 718 powder in a GE Concept Laser Xline 2000R printer. In the same build, a full-height downcomer was printed. Figure 9 shows the outcome of the effort.

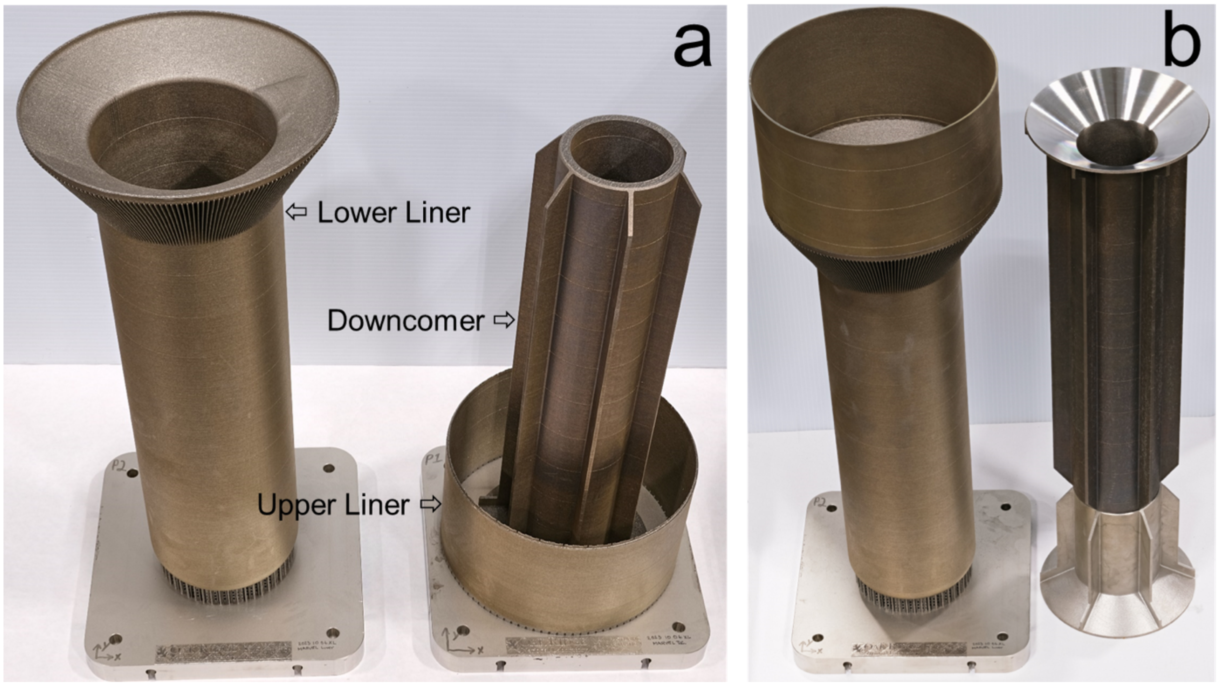

Figure 9: Full-height liner and downcomer printed simultaneously in a Concept Xline LPBF printer with a build time of 132 h. (a) Components immediately after printing attached to substrates, and (b) components partially removed from the substrates, machined, and assembled.

Results of blue light scans of the assembled full-height liner are shown in Figure 10. Deviation plots for several sections of the liner suggest that the as-printed liner generally fits into the existing IHX housing. Elliptical distortion of the liner diameter near the upper conical portion of the liner may result in some interference with the housing. Factors that likely contribute to this distortion include powder compaction and redistribution that may occur along the inclined edge of a tapered overhang.

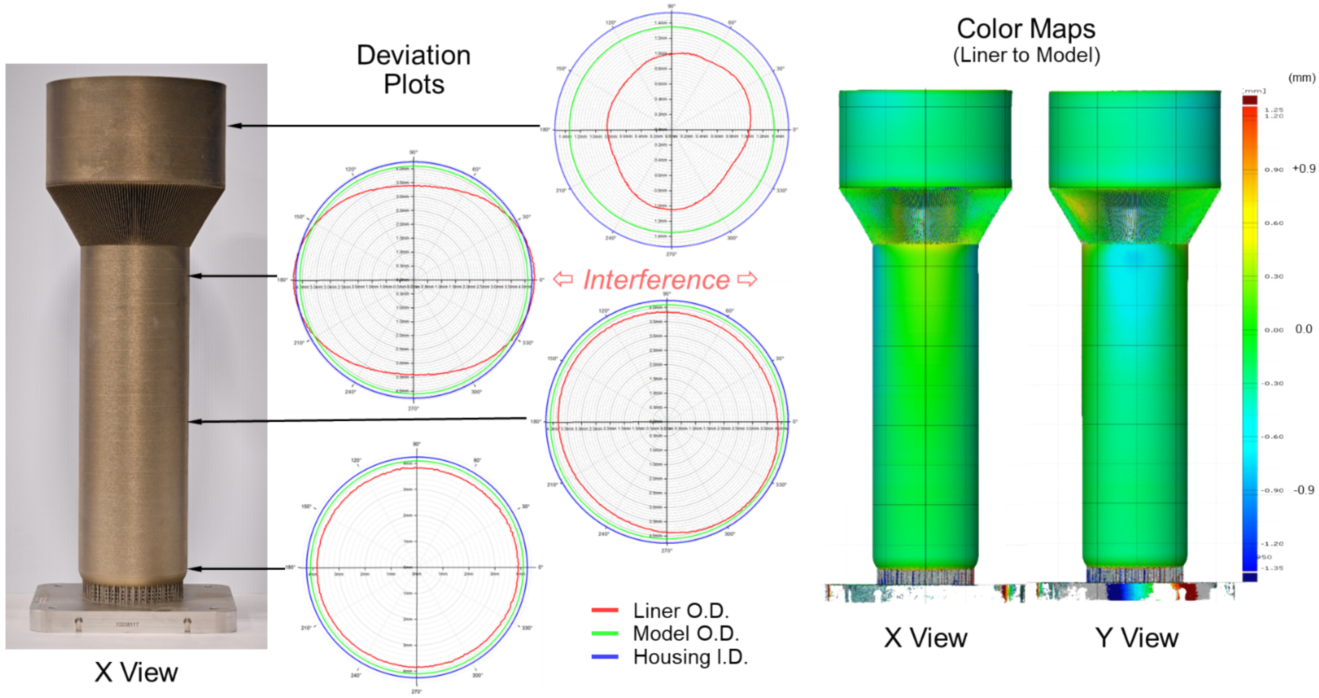

Figure 10: Blue light deviation plots and color maps for the full-height LPBF liner. Although the cross section of the liner is generally circular, elliptical distortions near the conical upper portion of the liner are sufficient to lead to mechanical interference with the IHX housing.

Another more direct manifestation of powder compaction and redistribution at the inclined edges of the tapered overhang is shown in Figure 11. The pair of “cat’s ears” toward the right side of the color map protrude more than 1 mm above the model surface. Lateral powder redistribution along the wiper front as the wiper approaches the inclined, tapered overhang is likely analogous to the formation of rip currents as ocean waves approach a sloping beach.[2–4] A consequence of the formation of such a local protrusion of the printed surface is the formation of a wake or local depletion of powder supply downstream of the protrusion. Low regions (blue streaks on a green background) are visible in the color map in Figure 11 on the inclined top surface of the liner that are opposite (i.e., to the left) and downstream (with respect to the wiper direction) of the “cat’s ears”. These regions are likely the result of this depletion of powder.

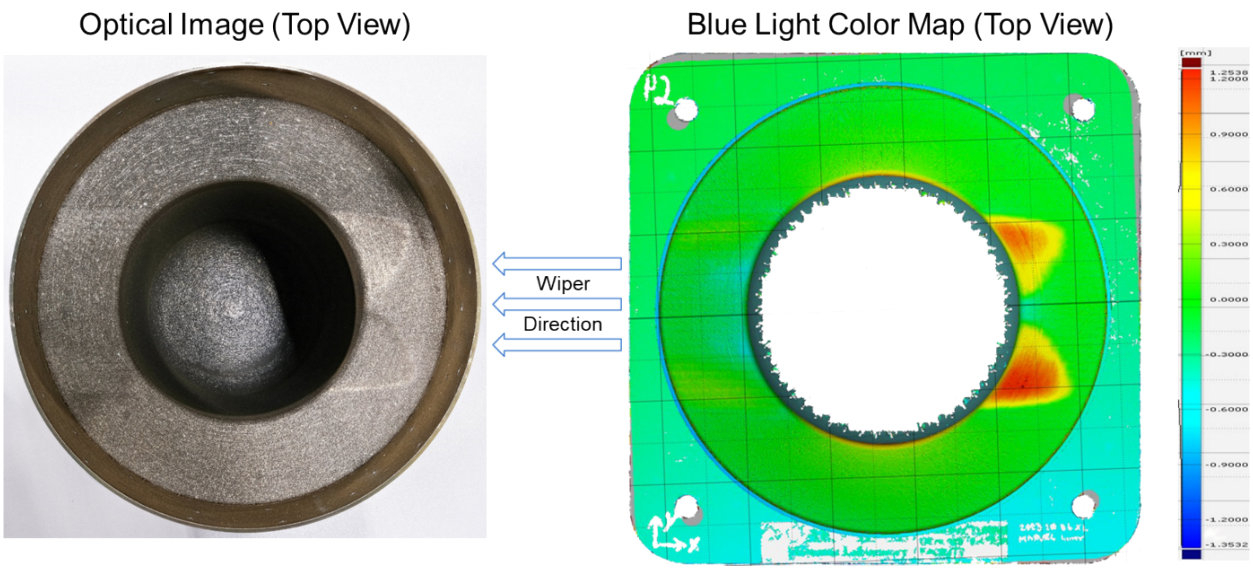

Figure 11: (left) Optical image and (right) corresponding blue light color map of the top of the full-height LPBF liner.

3. THOUGHTS AND CONCLUSIONS

Using various printers at the ORNL MDF, several approaches to fabricate a liner assembly for the IHX of the MARVEL microreactor have been pursued. An oversize, near-net-shape 316L LPBF liner has been printed and post-machined with excellent dimensional quality after machining. The times to print and machine this approximately one-third height liner were 109.5 h and 9.5 h, respectively. The dimensional quality is lower for attempts to print directly (without machining) net-shape liners by DED of 316L SS and by LPBF of Inconel 718, and improving the quality may be limited by the nature of the printing processes. These results for the printed liner contrast with those for the as-printed net-shape downcomers, for which the dimensional quality is likely sufficient to meet the functional requirements of the application without additional post-machining except for the removal of supports.

Based on the outcome of these preliminary fabrication efforts with respect to dimensional quality and rough estimates of printing and machining times, the most cost-effective path to a fully functional liner assembly is likely via five-axis CNC machining of solid wrought blanks of 316L SS. The estimated time to print a full-height, oversize liner preform by LPBF (~109.5×3 = ~328 h) far exceeds the estimated time to CNC machine a liner from a solid blank (~9.5×3×3 = ~85 h).

For a single downcomer, the estimated fabrication times are closer and probably within the margins of error. The estimated time to print a full-height LPBF downcomer is approximately 132–159 h (~53×3), whereas the estimated time to CNC machine a downcomer is close to that to machine a liner (~85 h). If multiple downcomers are printed simultaneously on a substrate (up to 10 for the Xline substrate), print times per downcomer will be dramatically less—perhaps as little as 20 h per downcomer.

For this specific application/demonstration (a liner assembly for the IHX of the MARVEL microreactor), a hybrid approach seems most attractive—an AM LPBF downcomer within a conventionally machined liner. The LPBF printer for the downcomer would need a minimum vertical capacity of approximately 425 mm and be loaded with 316L SS. Such a printer is not presently available at the ORNL MDF. For machining the liner, either a five-axis CNC machine or even a suitably sized lathe with a long reach (greater than approximately 425 mm) boring tool would likely suffice.

4. REFERENCES

1. Idaho National Laboratory, *Microreactor Applications Research Validation and Evaluation Project (MARVEL)*, 20-50248_MARVEL_Fact_Sheet_R15.pdf (inl.gov) 2022.
2. Dalrymple, R. A., J. H. MacMahan, A. J. H. M. Reniers, and V. Nelko. “Rip Currents.” *Annual Review of Fluid Mechanics* 43 (2011): 551–581. DOI: 10.1146/annurev-fluid-122109-160733.
3. Castelle, B., T. Scott, R. W. Brander, and R. J. McCarroll. “Rip Current Type, Circulation and Hazard.” *Earth Science Reviews* 163 (2016): 1–21. DOI: 10.1016/j.earscirev.2016.09.008.
4. Brander, R.W. (2015). “Rip Currents.” In *Sea and Ocean Hazards, Risks and Disasters*, edited by J. Ellis and D. Sherman, 335–380. Treatise in Hazards and Disasters. Elsevier, 2015.