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3D-Printed Dissolvable Molds for Rapid Fabrication and Replacement of Elastomeric Vehicle Parts

by Michael J. DeGrange, Derek J. Bischoff, and Eric D. Wetzel

NOTICES

Disclaimers

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14. ABSTRACT
Elastomeric parts are difficult to replace at the point-of-need due to the high capital investment and footprint required for injection molding. 3D-printed tooling is demonstrated in the production of a gladhand seal using minimal equipment, namely a 3D printer and cast-cure resin. The entire process from identification of a failed part to the successful installation of a replacement is completed in under 24 h. Evaluation of the replaced seal confirms its functionality. The designed mold files and associated documentation are uploaded to the Advanced Manufacturing Digital Repository as a resource for Army sustainment personnel.

15. SUBJECT TERMS
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Contents

List of Figures

List of Tables

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1. Introduction

The U.S. Army uses a variety of ground vehicles in critical missions where a nonfunctioning platform can risk mission success. With standard wear and tear, age, weathering, chemical exposure, and damage, elastomeric vehicle parts can become nonfunctional over time. Elastomeric vehicle parts are required for gaskets, seals, covers, and energy absorption and dissipation. The sustainment of vehicles in theater is often limited by the ability to rapidly replace these elastomer parts. Rapid replacement methods for elastomeric parts can be limited by long lead times for original equipment manufacturer (OEM) replacement parts, contested logistics, and high minimum-order quantities. There are currently no widely deployed technologies to allow sustainment units to fabricate the diverse range of necessary replacement parts in the field.

Some elastomeric parts with high Shore A hardnesses, e.g., above Shore 85A, may be directly 3D printed using inexpensive (<$1,000) commercially available filament extrusion 3D printers. However, lower hardness elastomers cannot be directly printed due to limitations in the filament feed mechanism leading to inconsistent extrusion, clogs, and ultimately print failure. A molding approach, where 3D printers fabricate tooling instead of the final part, can overcome this limitation using printers already deployed to military units. In this process, a thermosetting cast-cure resin is infused into the mold and cured. The tooling is then removed to yield the final part. The tooling is readily printed using material designed for additive manufacturing (AM) with high print speeds, typical temperatures, and good overhang performance. Using a sacrificial or fugitive mold that is simply dissolved or washed away can provide several advantages over traditional reusable molds. Sacrificial molds allow for simpler mold designs, allowing engineers to ignore draft angles, ejection pins, and parting line placement considerations. Dissolvable molds allow for the fabrication of more geometrically complex parts containing captive features, internal channels, and steep overhangs.

Previous work from our group demonstrated the use of sacrificial molds in the production of parts including a fiberglass-reinforced timing belt,[1] a resilient mount used in the family of medium tactical vehicles (FMTV) suspensions,[2] a bus bar cover assembly used in the Bradley A4 fighting vehicle,[2] multi-material interpenetrating lattices,[3] and energy-absorbing structures.[3] In these reports, we investigated various commercially available filaments that are readily printable on desktop filament 3D printers to produce the molds and the effect of the dissolving solvent on the cast part. We showed that water, broadly speaking, is the least aggressive toward the cast parts and therefore that water-soluble molds are well-suited for the production of a variety of parts from silicones, epoxies, and urethanes.

Butenediol vinyl alcohol (BVOH) filament was selected as the optimal mold material due to its rapid dissolution and lack of swelling upon immersion in water.[1]

Herein, the entire process from identifying a failed part to successful replacement is demonstrated with a gladhand seal on an FMTV-class vehicle. The functionality of the replacement part is evaluated. A time study is conducted on the entire fabrication process to understand the time required to replace elastomeric parts using the new methodology. The mold design and supporting documentation is uploaded to the Advanced Manufacturing Digital Repository (AdvM DR or AMDR) to allow sustainment units to rapidly access the files necessary to replace the part in the field. The AdvM DR serves as the Army's authoritative, centralized enterprise database for securely storing and sharing 3D printing files and technical data packages. Consolidating these files into a single location prevents the dangerous proliferation of unvalidated "digital islands" and ensures that every printed part is reliable, preventing duplicated efforts across units.

2. Experimental

2.1 Materials

Ultrafuse BVOH copolymer filament was obtained from BASF Forward AM (Heidelberg, Germany). Before printing, the material was dried in an oven at 60 °C for at least 24 h. The urethane PMC 770 (Shore 70A, $E_{100\%}$ = 1.72 MPa, ε_b = 750%, η = 3000 cps) was obtained from Smooth-On (Macungie, Pennsylvania). Doxy 5, a vacuum degassing agent, was also obtained from Smooth-On. All materials were used as received.

2.2 Mold Design and 3D Printing

2.2.1 Mold Design and Material Selection

The gladhand seal was removed from the vehicle (Figure 1) and measured using calipers (Figure 2) to determine the critical dimensions of the part. The gladhand seal is used in the brake line connecting the truck to the trailer. A stand-mounted durometer is used to determine the Shore hardness of the OEM urethane gasket as 70 A (Figure 1d). The National Stock Number (NSN) of the gladhand seal is 5330-00-172-1919.

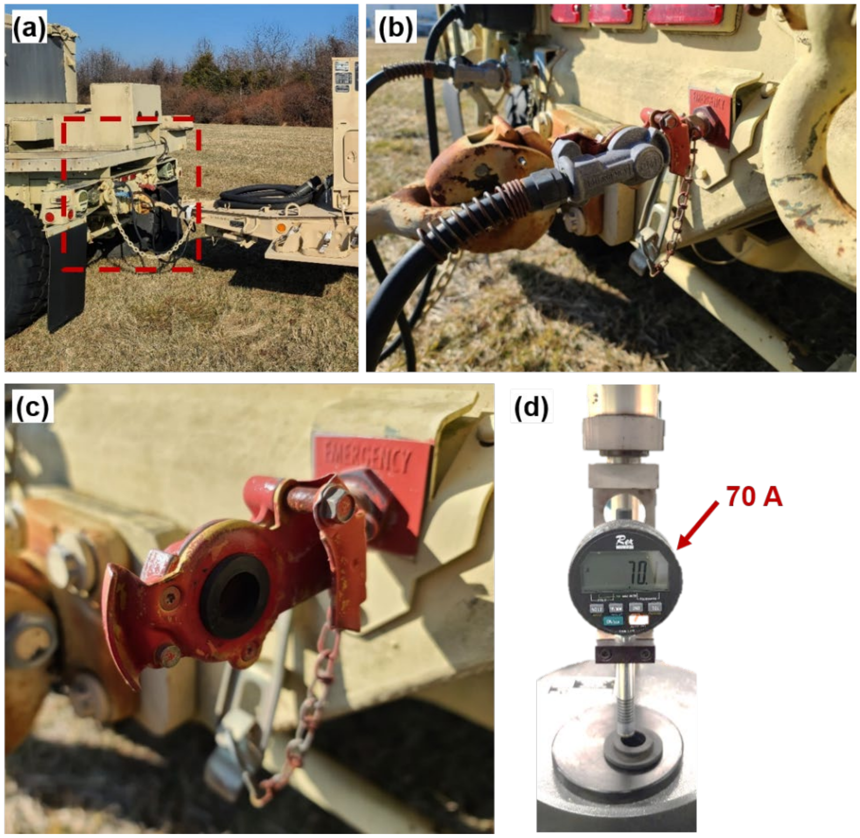

Figure 1. **Location of gladhand seal and OEM part removal. (a) location of the gladhand seal on the emergency brake pneumatic line for connecting a trailer, (b) emergency service gladhand, (c) OEM gladhand seal, and (d) determination of urethane Shore hardness.**

Figure 2. **Dimension measurements of the OEM gladhand seal taken off the vehicle. (a) total thickness, (b) inner diameter (ID), (c) outer lip thickness, (d) outer diameter (OD), and (e) inner lip diameter.**

A CAD model for the gladhand seal was developed in SolidWorks 2025 (Dassault Systèmes, Vélizy-Villacoublay, France). The resulting CAD model (Figure 3) of the gladhand seal was used to construct the mold (Figure 4). The part was placed at a 7.4° angle inside the mold to eliminate large overhangs that would cause the print to fail. The top surface of the part is connected to the outlet port using a runner of 3.18 mm diameter. The bottom surface of the part is connected to the inlet port using a runner of 3.18 mm diameter. To reduce the amount of BVOH used to fabricate the mold, a 12.5-mm-diameter bore is placed in the middle of the mold inside of the 18.5-mm ID of the gladhand seal. The two ports are designed to accept a push-to-connect fitting with polytetrafluoroethylene (PTFE) tape wrapped 6.35-mm (1/4-inch) Unified National Fine (UNF) threads. The port's diameter tapers from 12.7 to 11.52 mm over a distance of 19.07 mm. The position of the ports and angle of the part in the mold is designed to minimize the likelihood of trapped air in the cast part by encouraging a resin flow front that steadily rises vertically during fill to push any air in the mold out through the mold's outlet port.

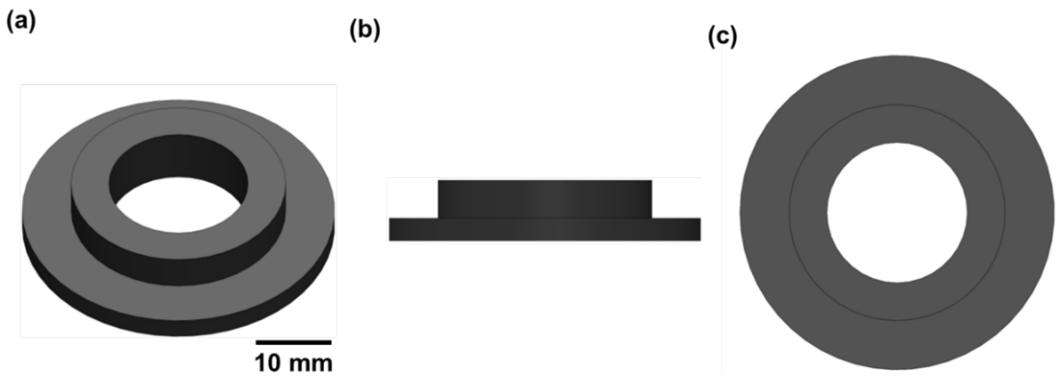

Figure 3. Model of the gladhand seal taken from the vehicle (a) angled view, (b) side view, and (c) top view.

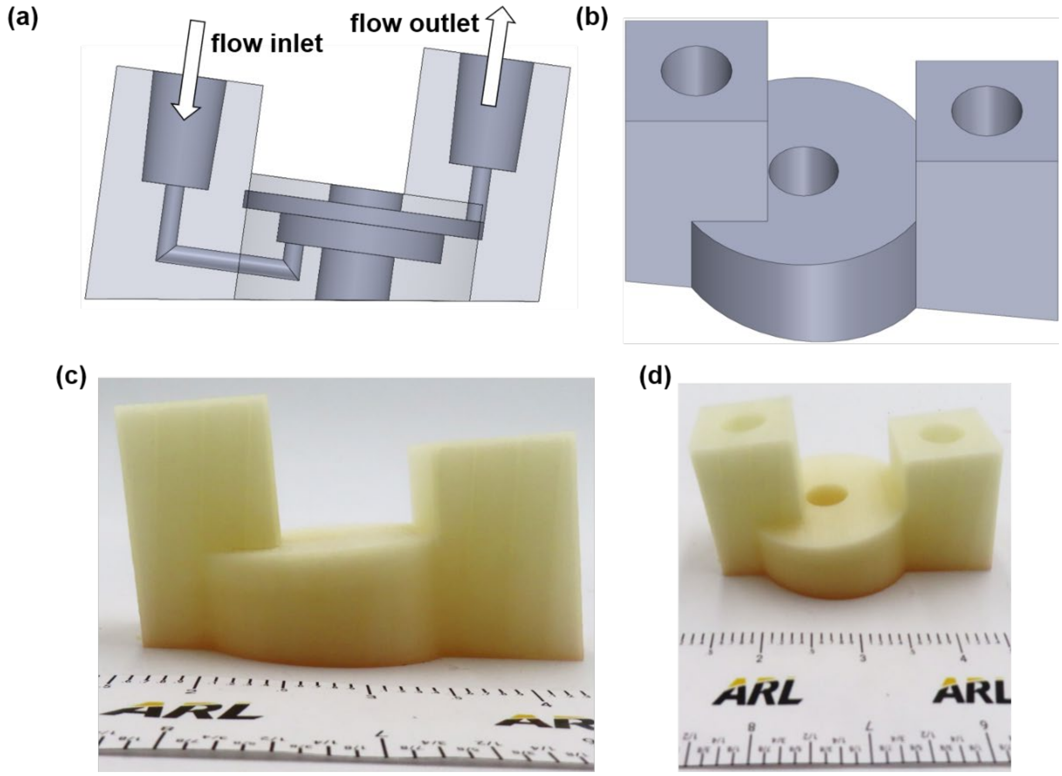

Figure 4. Gladhand seal mold. (a) CAD model side view with transparency, (b) CAD model at an angle, (c) 3D-printed mold side view, and (d) 3D-printed mold at an angle.

2.2.2 Slicing and 3D Printing

The STL models generated from the CAD software were imported into PrusaSlicer 2.9.0 for slicing using the 0.20-mm structural preset print settings with a modified Verbatim BVOH filament profile. A 3-mm brim with a 0-mm offset from the part was added to aid in bed adhesion of the model at the corners to prevent warping and the number of perimeters was set to three to reduce the leaking of resin into the infill. The parts used 15% gyroid infill density. The number of top and bottom surfaces were set to five. Dynamic overhang speed was used to reduce speeds in these areas to 5 mm/s for all overhang percentages. The print temperatures for BVOH were 225 °C for the nozzle and 60 °C for the bed. Molds were 3D printed using 1.75-mm filament on an MK4 from Prusa Research (Prague, Czech Republic) equipped with a 0.4-mm brass nozzle. Print speeds ranged from 45 mm/s on external perimeters to 140 mm/s for internal infill, and the extrusion width is 0.45 mm. During printing, the BVOH spool was kept in a dry box (PrintDry Filament Dryer PRO3) at 65 °C to prevent the hygroscopic filament from absorbing moisture. The mold took approximately 2.25 h to print and used 30 g of filament.

2.3 Resin Infusion and Release from Mold

PTFE tape was wrapped around the 6.35-mm (1/4-inch) UNF threads of two push-to-connect fittings for 9.525-mm (3/8-inch) OD rigid tubing. The two fittings were threaded into the ports of the mold. Following manufacturer's guidelines for the Shore 70A urethane resin, parts A and B were mixed in a 2:1 weight ratio inside a disposable beaker so that the total volume of resin is approximately 60 mL, significantly more than that of the volume needed solely to fill the cavity. For every 500 g of the mixed casting resin, 0.25 g of Doxy 5 were added. The combined material was vacuum degassed for approximately 10 min until most of the bubbles were removed. The resin was then transferred to a disposable syringe with a 9.525-mm (3/8-inch) OD, 6.35-mm (1/4-inch) ID length of disposable tubing as the nozzle. A vacuum pump with an in-line resin trap was connected to the mold's outlet port.

A tubing clamp was applied to the inlet tubing, between the syringe and the mold, and the vacuum was engaged to evacuate the mold. After evacuation, the clamp is removed and resin begins to flow from the syringe. Additional pressure applied by pushing the plunger causes the resin to flow faster. Flow is maintained until the entire mold is filled, as determined by a bubble-free, steady flow of resin from the outlet port into the resin trap. At this point, the vacuum is turned off and after the vacuum gauge returns to atmospheric pressure, the inlet tubing is clamped and the two tubing runs are cut with scissors to allow the filled mold to be transferred to a 2.5-gal pressure pot (California Air Tools, San Diego, California) maintained at 60 psi and room temperature during cure. The segment of tubing remaining at the outlet is left unclamped in a vertical orientation above the mold. Any shrinkage of the resin due to bubble collapse in the pressure pot is backfilled from resin in the tubing. The 70A urethane cures for 16 h.

Following cure, the clamp is removed and the tubing runs are cut off from the molds prior to submerging the molds in a reservoir of stirring warm tap water (UltiMaker PVA Removal Station, Utrecht, The Netherlands). After releasing from the mold, the parts are dried and the sprues on the inlet and outlet are cut off to yield the final gladhand seal.

3. Results

3.1 Resulting Seal

The cast seal both geometrically and mechanically matches the OEM seal. The OEM seal appears slightly warped in Figure 5 due to prior use, whereas the newly cast sample lies flat. Both gladhand seals were installed similarly onto the vehicle (Figure 6) and provided a good fit with the brake line gladhand. The durometer of the cast part was measured and found to be 69.5A.

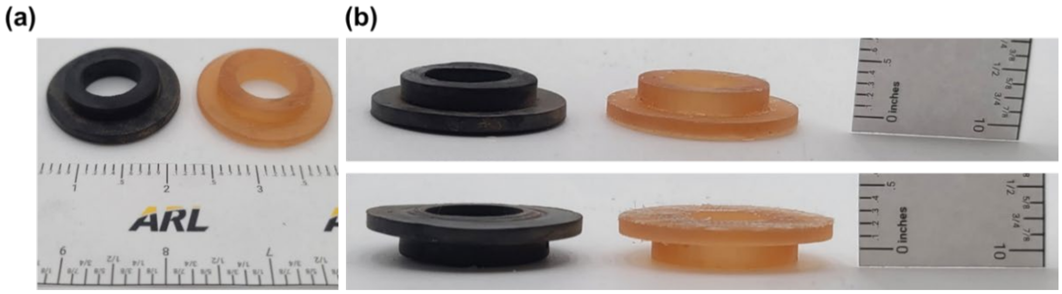

Figure 5. Comparison of OEM (black) and cast gladhand seal: (a) angled and (b) side views.

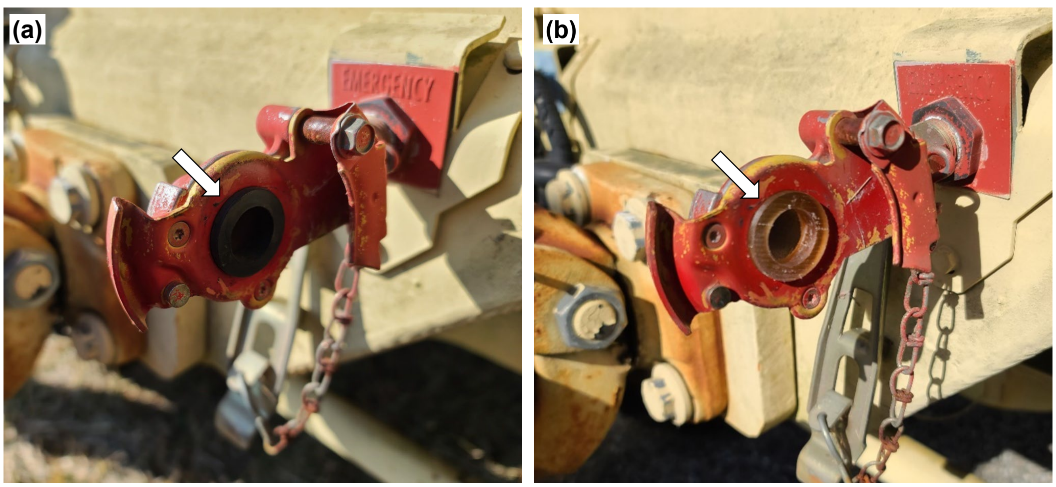

Figure 6. Comparison of OEM (black) and cast gladhand seal: (a) OEM and (b) cast seals installed.

3.2 Process Time Study

To understand the process time involved with replacing a malfunctioning part, a U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) mechanical engineer trained in CAD and 3D printing recorded the amount of time elapsed during each step in the part replacement process (Table 1). The study started after identifying the gladhand seal as the malfunctioning part. The study took place between Monday and Tuesday to strategically position the cure time during nonworking hours overnight. Of all the steps listed, the resin cure was the longest, but it is a passive operation requiring no operator attention. Additionally, the 3D printing and dissolution steps are also passive and can occur in the background while the operator is working on other tasks. The newly cast replacement seal was successfully installed on the vehicle within less than 24 h of identifying the faulty part. The total labor time is estimated to be less than 2 h.

Table 1. Time study results.

Step	Start time	Elapsed time (min)	Cumulative time (min)	Labor time (min)
Remove seal from truck	1250 Monday	10	10	10
Measure seal and Shore hardness	1300	5	15	5
Design mold in CAD	1305	25	40	25
Print mold with BVOH	1330	170	210	10
Mix resin and degassing aid	1620	17	227	17
Vacuum degas resin	1637	10	237	10
Infuse resin into mold	1647	6	243	6
Cure resin	1653	977	1220	5
Dissolve mold	0910 Tuesday	70	1290	10
Install new seal on truck	1030	10	1300	10
Total	**21 h 40 min**	**. . .**	**1300**	**108**

3.3 Testing Function of Gladhand Seal

To test for leaks, Windex was sprayed on the installed gladhand seal. The trailer brake lines were then pressurized and the seal was visually inspected for bubbles, which would indicate a leak. The presence of bubbles in the liquid would indicate an incomplete pneumatic seal, such as those observed in Figure 7a. The typical line pressure in the brake system is in excess of 100 psi. With the cast gladhand seal installed on the service line and the brake foot pedal pressed, the line was successfully pressurized and no leaks were observed in Figure 7b.

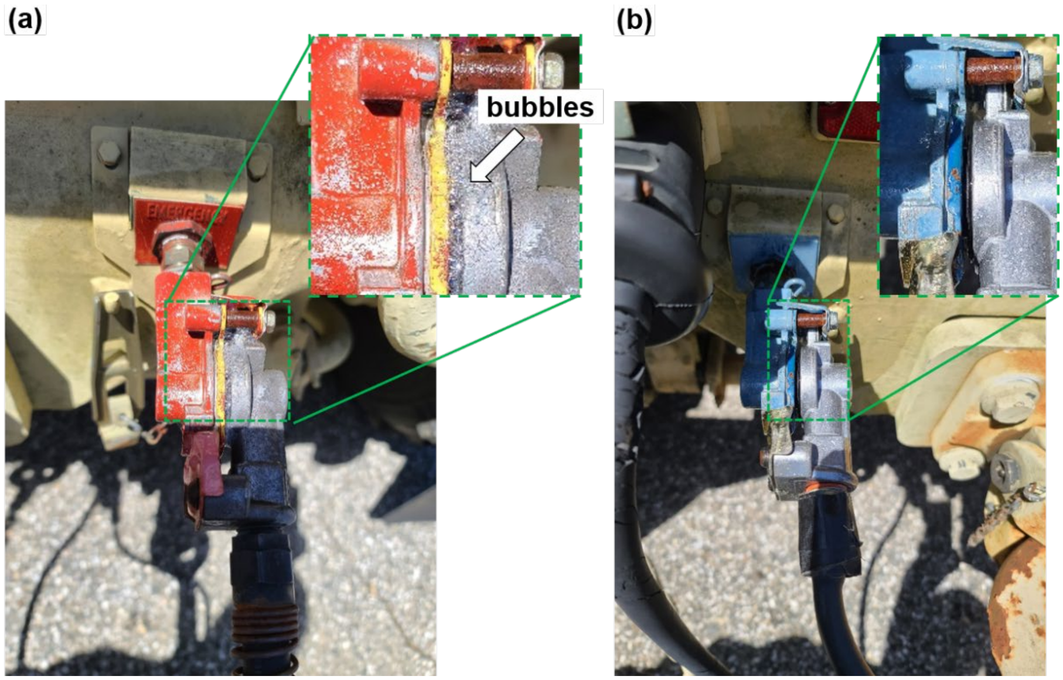

Figure 7. Gladhand seal leak test: (a) failed leak test for OEM seal causing bubbles to form and (b) successful leak test for cast seal resulting in no bubbles.

3.4 Uploading Tooling Design to AdvM DR

The mold design was uploaded to the AdvM DR to disseminate to units and other end users. Uploading the part was straightforward and required filling out several fields about the part including a material description, 3D-printer type, filament type, NSN, and supporting documentation providing more details on print settings, print orientation, etc. The mold is available on the AdvM DR with the title "Gladhand seal for EQ-36 FMTV."

4. Conclusions

We rapidly fabricated a gladhand seal for an FMTV using 3D-printed, dissolvable molds. This method allows for the creation of a part from a resin that is not suitable for direct 3D printing and requires only minimal equipment. Careful mold design is employed to position the ports at locations on the part to allow air to escape, leading to fully dense parts. Upon review we saw that our mold design was flawed. Due to printing the part at a 7.4° angle, the inlet and outlet were not at the lowest and highest points of the mold cavity, respectively. We fixed this by rotating the part –7.4° instead, as shown in the final design in Figure 8.

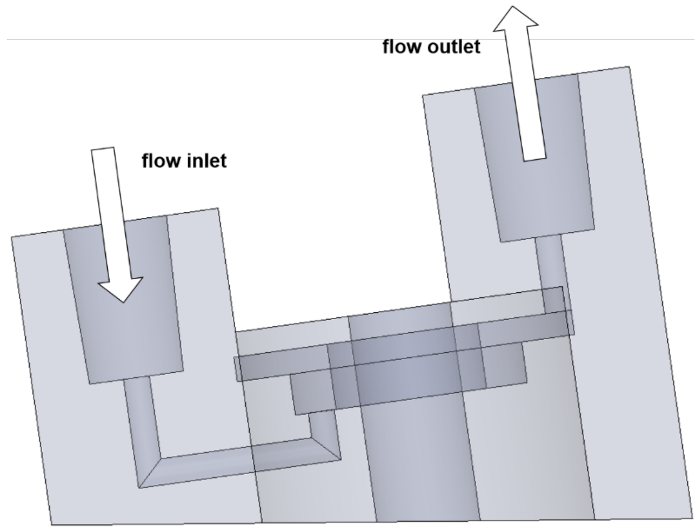

Figure 8. Corrected mold design flow inlet is at the lowest point of the cavity.

3D-printed tooling is demonstrated to rapidly return a disabled vehicle to service in less than 24 h. The replacement seal is demonstrated to function as intended and did not leak. The STL of the mold is uploaded to the AdvM DR to provide the widest dissemination across Army units along with a set of work instructions to assist with fabricating at the point-of-need. Overall, this approach provides a route to manufacture small batch and one-off parts that would otherwise be extremely costly with long lead times.

5. References

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List of Symbols, Abbreviations, and Acronyms

3D	Three-Dimensional
AdvM DR or AMDR	Advanced Manufacturing Digital Repository
AM	Additive Manufacturing
ARL	Army Research Laboratory
BVOH	Butenediol Vinyl Alcohol
CAD	Computer-Aided Design
DEVCOM	U.S. Army Combat Capabilities Development Command
FMTV	Family of Medium Tactical Vehicles
ID	Inner Diameter
NSN	National Stock Number
OD	Outer Diameter
OEM	Original Equipment Manufacturer
PTFE	Polytetrafluoroethylene
UNF	Unified National Fine

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