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Fabrication of Low Durometer Vehicle Parts via 3D-Printed Dissolvable Molds

by Derek J. Bischoff, Michael J. DeGrange, Matthew P. Ludkey, Anthony M. Clay, and Eric D. Wetzel

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14. ABSTRACT
3D-printed dissolvable molds are used to fabricate low durometer parts (90A and 70A Shore hardness) required for Army ground vehicles using castable, curing polymer resins that are not amenable to direct 3D printing. Butenediol vinyl alcohol copolymer, a water-soluble polymer feedstock material for fused filament fabrication 3D printing, is used to fabricate molds for ground vehicle parts. After infusing the molds with thermosetting polyurethane resins, the material cures and the mold is dissolved in water to yield the final part. Gas-pressurized chambers are used to infuse the molds and ensure low voids in the part after cure. This approach shows promise for rapidly producing vehicle parts from material feedstocks that cannot be directly 3D printed at the point of need.

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ground vehicle, dissolvable mold, 3D printing, fused filament fabrication, FFF, casting, molding, advanced manufacturing, expeditionary manufacturing, point-of-need manufacturing, Sciences of Extreme Materials

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1. Introduction

Previous work from our group has demonstrated the use of sacrificial molds in the production of parts including fiberglass-reinforced timing belts,[1] multi-material interpenetrating lattices,[2] and energy absorbing structures.[2] In these reports, we have investigated various commercially available filaments to produce the molds and the effect of the dissolving solvent on the casted part. We have shown that water, broadly speaking, is the least aggressive towards the casted parts, and therefore that water-soluble molds are well-suited for the production of a variety of parts from silicones, epoxies, polybutadiene rubbers, and urethanes. Butenediol viny alcohol (BVOH) filament was selected as the optimal mold material due to its rapid dissolution and lack of swelling upon immersion in water[1] in addition to its rapid print speed and improved temperature resistance. The mold design process is simplified compared to traditional separable molds. For example, consideration of draft angles and the positioning of parting lines is not necessary with a dissolvable mold. Similarly, ejector pins or mold release is not necessary to obtain the molded part.

Herein, 3D printing is used to create molds for three elastomeric parts used in ground vehicles, where the molds are created from digital design files (STL format) provided by the U.S. Army Combat Capabilities Development Command (DEVCOM) Ground Vehicle Systems Center (GVSC). The parts include 1) a resilient mount, also referred to as the rear stabilizer bar rubber mount bushing, used in the Family of Medium Tactical Vehicles (FMTVs) and various military trucks and 2) two subparts used in a bus bar cover assembly on Bradley A4 fighting vehicles. The molds are produced using BVOH, and the parts are cast using polyurethane resins with durometers of 90A and below. Compared to prior reports, two process improvements have been undertaken. First, resin transfer into the mold is completed using a gas-pressurized reservoir, which allows for faster filling and more viscous resins compared to manual resin injection with a syringe. Second, cure is performed inside of a gas-pressurized chamber to collapse bubbles and reduce void content. The fabricated parts are then test fit on both an FMTV and a Bradley A4 fighting vehicle to determine their applicability as replacements for original equipment manufacturer (OEM) parts.

2. Experimental

2.1 Materials

Ultrafuse BVOH 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 urethanes PMC 790 (90A, $E_{100\%}$ = 4.41 MPa, ε_b = 550%, η = 3000 cps) and PMC 770 (70A, $E_{100\%}$ = 1.72 MPa, ε_b = 750%, η = 3000 cps) were 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

The resilient mount (NSN: 5342-01-369-0893) and bus bar cover assembly (NSN: 5340-01-686-6056) parts to be molded are shown in Figure 1. The bus bar cover assembly is two sub-parts designated Part 1 and Part 2. These two parts are designed to come together, forming a shell around a high-power electrical lug assembly, while being secured with hose clamps. The resilient mount is to be casted from a 90A durometer urethane, and the bus bar cover assembly is to be casted from a 70A durometer urethane.

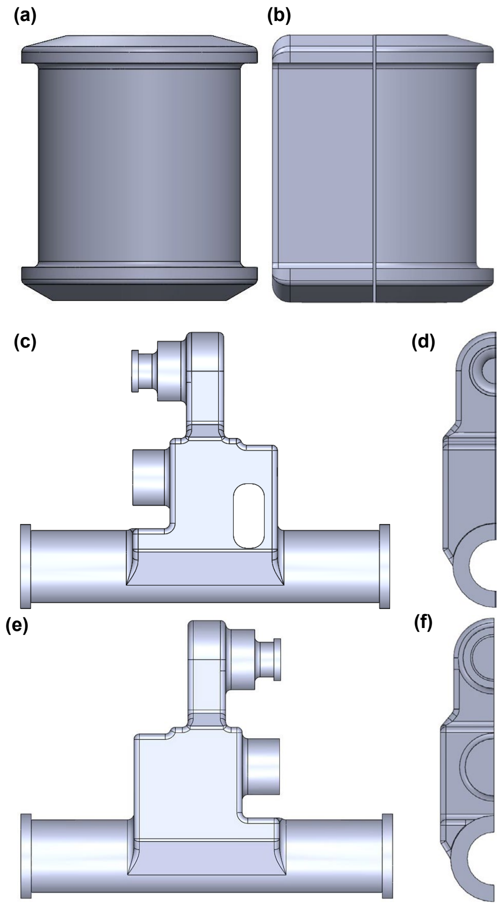

Figure 1. (a) Front view of the resilient mount, (b) side view of the resilient mount, (c) front view of Part 1 of the bus bar cover assembly, (d) side view of Part 1 of the bus bar cover assembly, (e) front view of Part 2 of the bus bar cover assembly, and (f) side view of Part 2 of the bus bar cover assembly.

2.2.1 Resilient Mount

A mold for the resilient mount (Figure 2) was designed in SolidWorks 2024 using the STL files provided by GVSC. Because the negative mold of the part must be directly printed, the flat top of the part would become a long bridging feature in the mold that would be difficult to print without support. To overcome this challenge, the part is oriented at a 45° angle relative to horizontal to convert the bridges to overhangs that are printable. Two tapered ports, decreasing from 9.9 to 5 mm over a 22-mm distance, are added to interface with 9.53-mm (3/8-inch) outer diameter (OD), 6.25-mm (1/4-inch) inner diameter (ID) disposable tubing. The ports connect to the part in the bottom front and the top back to ensure resin flows into the entire volume and pushes air out of the mold without trapping an air pocket. The volume of resin required to fill the mold is approximately 240 mL.

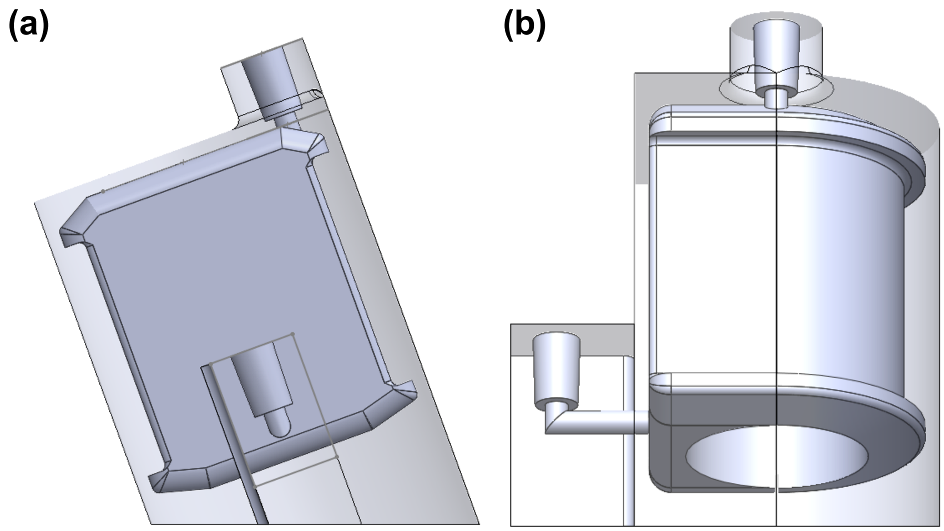

Figure 2. Resilient mount mold: (a) front view of the mold and (b) side view of the mold.

2.2.2 Bus Bar Cover Assembly

A mold (Figure 3) for the bus bar cover assembly was designed in SolidWorks 2024 using the STL files provided by GVSC. This assembly is made up of two parts that are individually molded to allow for the installation around a power distribution board. Because the negative mold of the parts must be directly printed, the flat portions of the parts would become long bridging features that would be difficult to print. To overcome this challenge, the parts are placed at a 45° angle relative to horizontal to convert the bridges to overhangs that are printable. The three support structures on the back side of the mold used to support the mold at 45° are designed as a separate body to enable multi-material printing. This section can be printed from polylactic acid instead of BVOH to reduce material costs. Two tapered ports, decreasing from 9.9 to 5 mm over a 22-mm distance, are added to interface with disposable tubing (9.53-mm OD, 6.25-mm ID). The inlet port connects to the part at the lowest point in the front of the mold, and the outlet attaches at the highest part in the back of the mold to ensure resin flows into the entire volume. The volume of resin required to fill each of the two molds is approximately 50 mL.

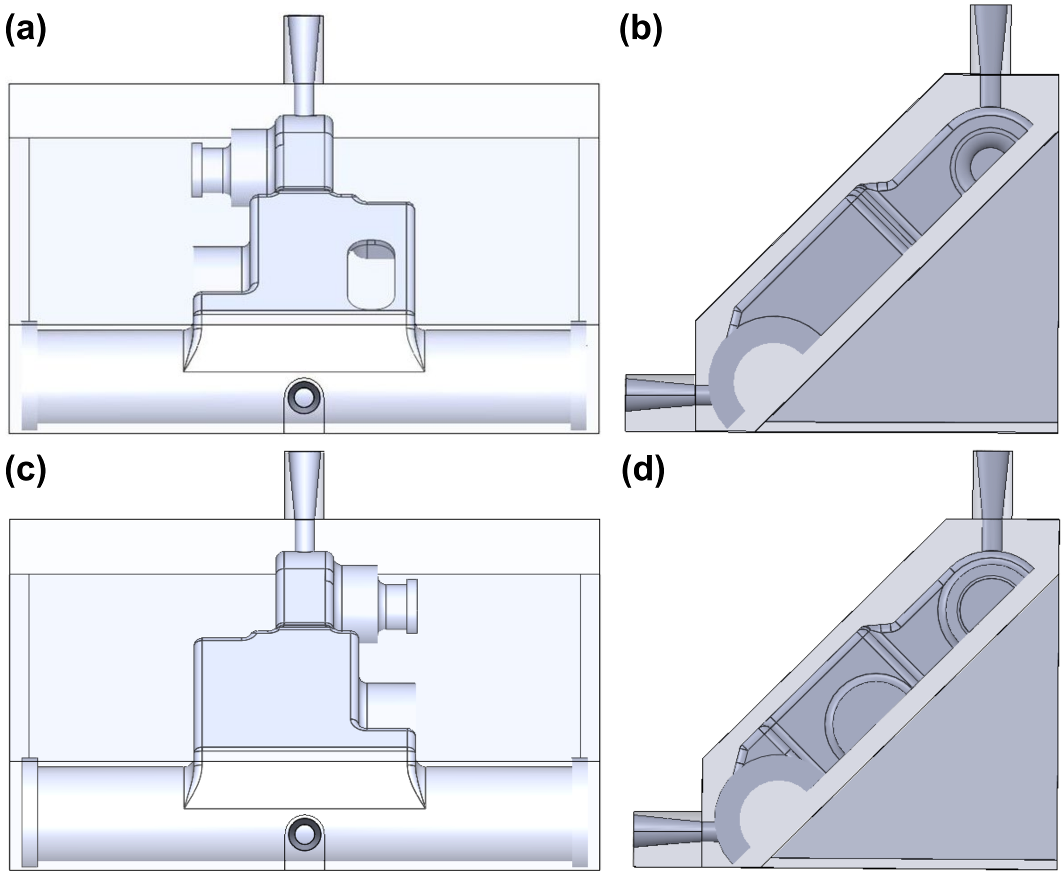

Figure 3. Bus bar cover assembly mold: (a) bus bar cover assembly Part 1 mold front view, (b) bus bar cover assembly Part 1 mold side view, (a) bus bar cover assembly Part 2 mold front view, and (b) bus bar cover assembly Part 2 mold side view.

2.2.3 Slicing and 3D Printing

The mold STL models generated from the CAD software were imported into PrusaSlicer 2.7.4 for slicing using the 0.20-mm structural preset print settings with a modified Verbatim BVOH filament profile (Figure 4). 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 because the large surface area of the gyroid enables rapid dissolution. The number of top and bottom surfaces was 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 a 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 at 75 °C to prevent the hygroscopic filament from absorbing moisture. The resilient mount took approximately 16 h to print (224 g), Part 1 of the bus bar cover assembly took approximately 29 h to print (422 g), and Part 2 of the bus bar cover assembly took approximately 29 h to print (422 g).

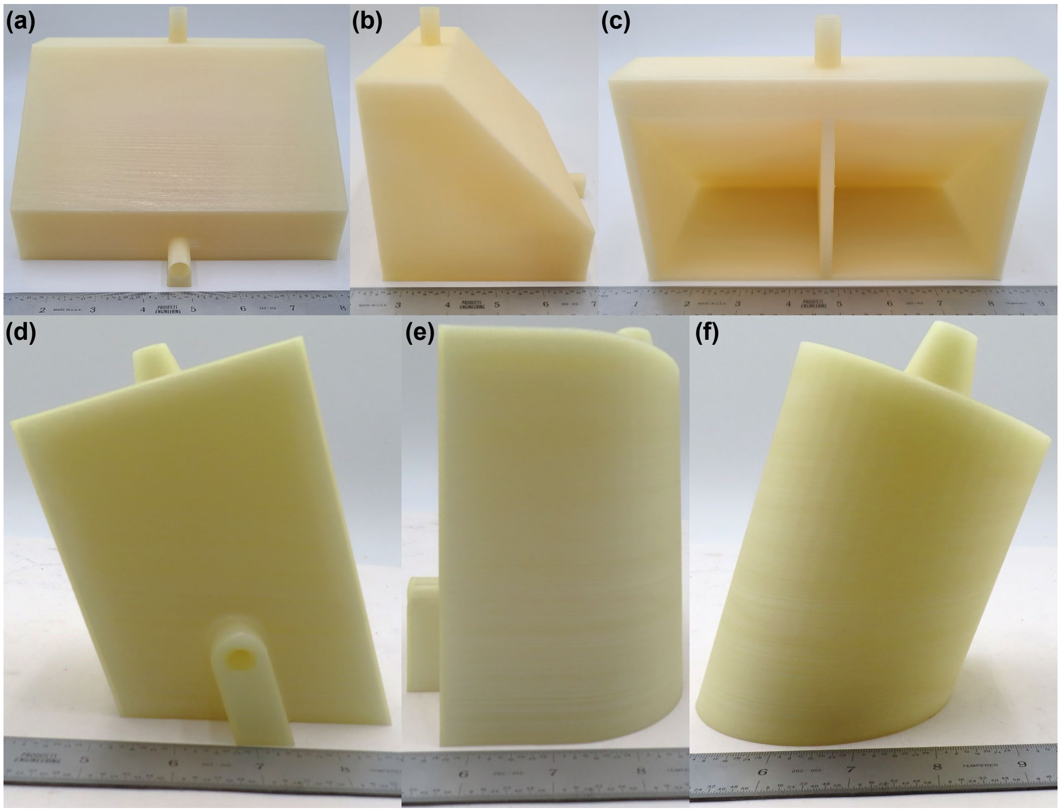

Figure 4. 3D-printed BVOH molds for the bus bar cover assembly and resilient mount: (a) bus bar cover assembly mold front view (Parts 1 and 2 are identical from an external view), (b) side view, (c) rear view, resilient mount front view, (e) side view, and (f) rear view.

2.3 Resin Infusion and Release from Mold

Following manufacturer guidelines for both the 90A and 70A urethane resins, Parts A and B were mixed in a 2:1 weight ratio inside a disposable liner (Figure 5a) so that the total volume of resin is approximately 2.5 times 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 was added. The disposable liner was a 7.57 L (2 gal) polyethylene bottle that had been cut to remove the narrowing section and cap. A piece of tape was added to the outside of the liner to enable lowering and raising it within the pressurized reservoir (described below, Figure 5b). The liner was chosen to maximize the resin surface area during degassing. The combined material was vacuum degassed for approximately 10 min until the majority of bubbles were removed. The liner was then transferred to the reservoir of a 2 L dispense system (Integrated Dispensing Solutions, Agoura Hills, California). Disposable tubing

(9.53-mm OD, 6.25-mm ID), rated for pressures over 690 kPa (100 psi), was inserted through the reservoir lid using a bored-through double ferrule (9.53 mm) compression fitting into the liner at the bottom of the resin. A triangular cut was made in this end of the tubing to ensure a constant flow of resin by preventing the tube from getting stuck to a side wall of the liner (Figure 5c). The other end of the tube was inserted into the mold tapered inlet port via an interference fit. A vacuum pump with an in-line resin trap was connected to the mold's outlet tapered port. Tacky tape was used to ensure a vacuum-tight seal between the tubing and the tapered ports (Figure 5d).

A tubing clamp was applied to the inlet tubing section, and the vacuum was engaged to first evacuate the mold. After evacuation, the clamp was removed and resin began to flow when the reservoir containing the liner was pressurized to approximately 552 kPa (80 psi). Flow was maintained until the entire mold was filled, as determined by a bubble-free, steady flow of resin from the outlet port into the resin trap. The mold was picked up and rotated to help bubbles trapped in the corners of the mold break free. At this point, the vacuum was turned off, and after, the vacuum gauge returned to atmospheric pressure and the reservoir was depressurized, which stops all resin flow. The outlet tubing remained unclamped and was positioned above the mold to allow resin to backfill into the mold as the resin retracted, relaxed, or shrank during cure. The inlet tubing was clamped, and the two tubing runs were cut with scissors to allow the filled mold to be transferred to a 9.5-L (2.5-gal) pressure pot (California Air Tools, San Diego, California) maintained at 414 kPa (60 psi) and room temperature during cure (Figure 5e). The 90A urethane cures for 48 h, and the 70A urethane cures for 16 h.

Following cure, the clamp was removed and the tubing runs were cut off from the molds prior to submerging the molds in a reservoir of stirring water shown in Figure 5f (UltiMaker PVA Removal Station, Utrecht, The Netherlands). Using hot tap water and the high agitation setting can reduce dissolution time to approximately 3 h for the parts. After releasing from the mold, the parts were dried and the sprues on the inlet and outlet were cut off to yield the final parts.

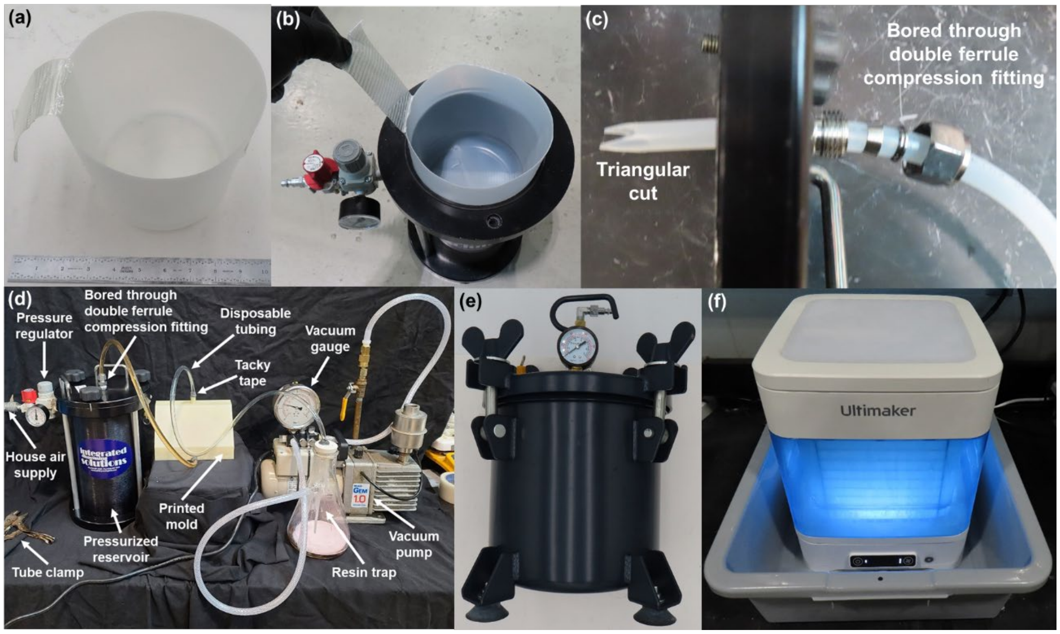

Figure 5. (a) Disposable polyethylene liner with tape handle, (b) liner being lowered into pressurized reservoir, (c) triangular cut in tubing and reservoir lid configuration, (d) resin infusion setup, (e) pressure pot used to reduce voids during cure at room temperature, and (f) mold dissolution via submersion in water.

3. Results

3.1 Resilient Mount

The results for the casted 90A resilient mount are shown in Figure 6. The BVOH readily dissolved in water in approximately 3 h owing to the part's large, exposed walls. BVOH contained in the thin slit section required the most time to dissolve. After most of the mold dissolved, mechanically separating the resilient mount at the slit greatly reduced the amount of time required to dissolve the BVOH contained in the slit. The slit down the length of the part was captured in the produced part, which allows the mount to be installed onto the vehicle. A high tear strength material is required during the installation because the mount needs to clamp onto the sway bar. The 90A urethane has a Die C tear strength of 53 N/mm.

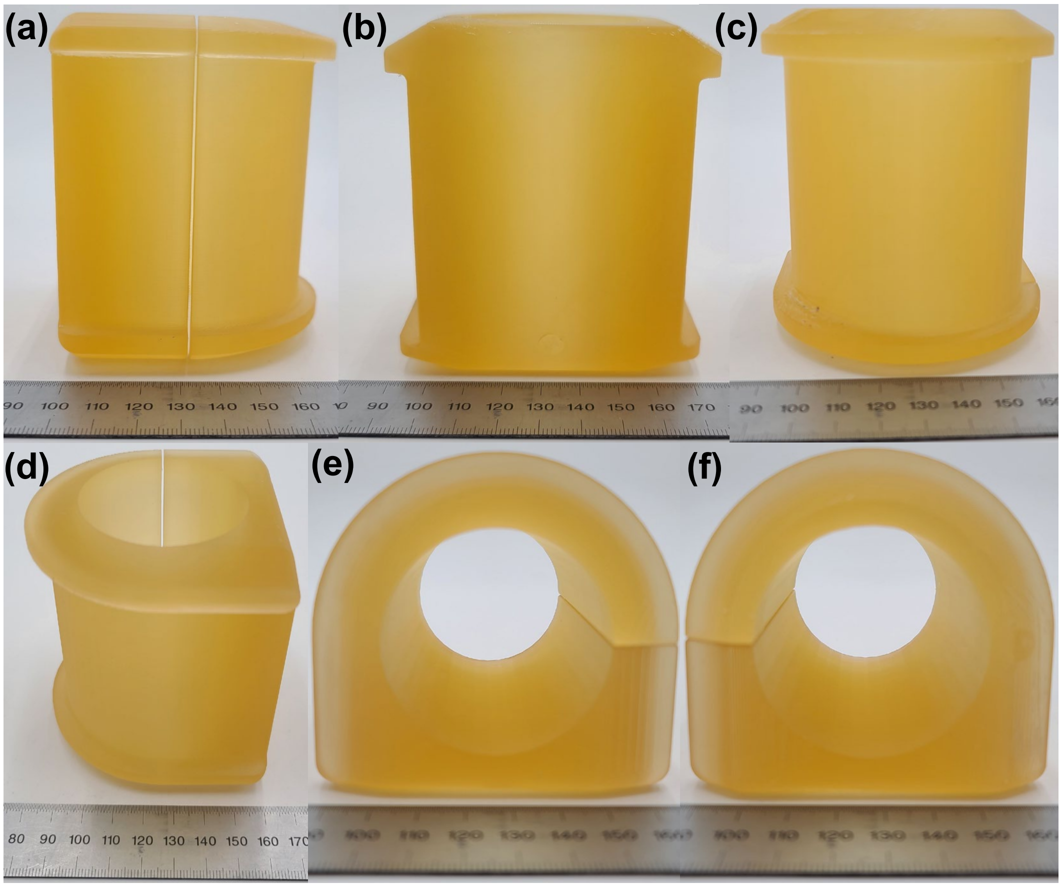

Figure 6. Images of the fabricated resilient mount from all sides: (a) left side view, (b) back view, (c) right side view (d) front view, (e) top view, and (f) bottom view.

Figure 7 shows the results of a fit test of the resilient mount on an FMTV. Figure 7a shows the rear torsion stabilizer sway bar. This stabilizer bar reduces the vehicle's tendency to roll when turning and helps keep more of the tires in contact with the road. The resilient mount is also referred to as a sway bar bushing. Figure 7b reveals the black OEM resilient mount after partially disassembling the sway bar. Figure 7c is a side-by-side comparison of the OEM and molded resilient mounts. Figure 7d shows the molded mount installed on the sway bar after spreading it apart to slide it over the sway bar. Figure 7e shows the complete installation of the molded mount on the sway bar. Figure 7e shows the FMTV during a 1.6-km drive with the molded resilient mount installed. During the test drive, the operator noted that there was no notable difference in the performance of the OEM part compared to the molded part.

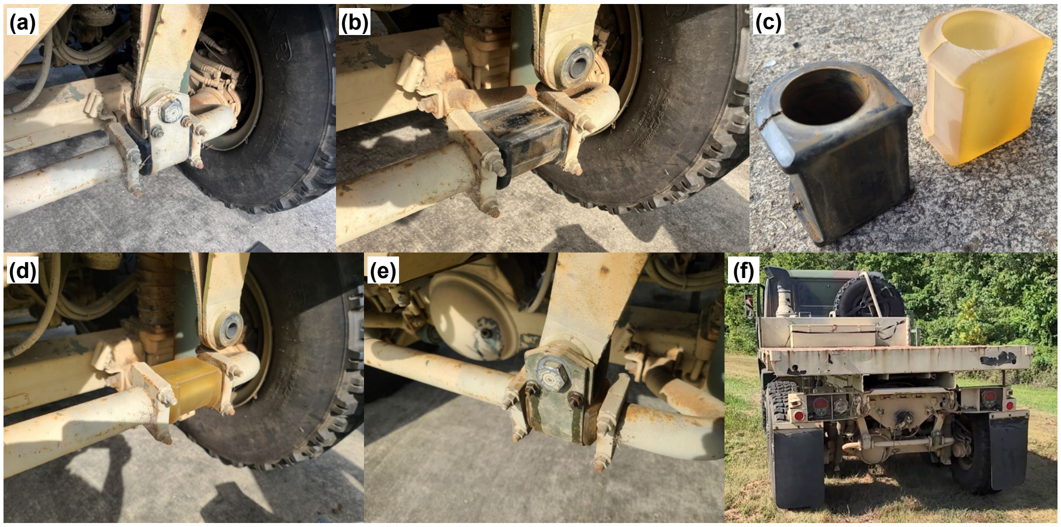

Figure 7. Resilient mount test fit on vehicle: (a) rear torsion stabilizer sway bar, (b) partial disassembly with black OEM resilient mount visible, (c) comparison between OEM part and molded part, (d) partially installed molded resilient mount, (e) fully installed resilient mount, and (f) FMTV driving with molded resilient mount installed.

3.2 Bus Bar Cover Assembly

The results for the two bus bar cover assembly subparts are shown in Figure 8. The two vestiges, where the inlet and outlet ports were connected, are visible on the final part as a consequence of positioning them on a curved surface that makes it difficult to make a flush cut. These two features, however, do not interfere with the functionality of the cover assembly and permit the two halves to be secured together. The assembled bus bar cover assembly, secured together using zip ties, is shown in Figure 9. The two halves come together without any significant geometrical mismatch.

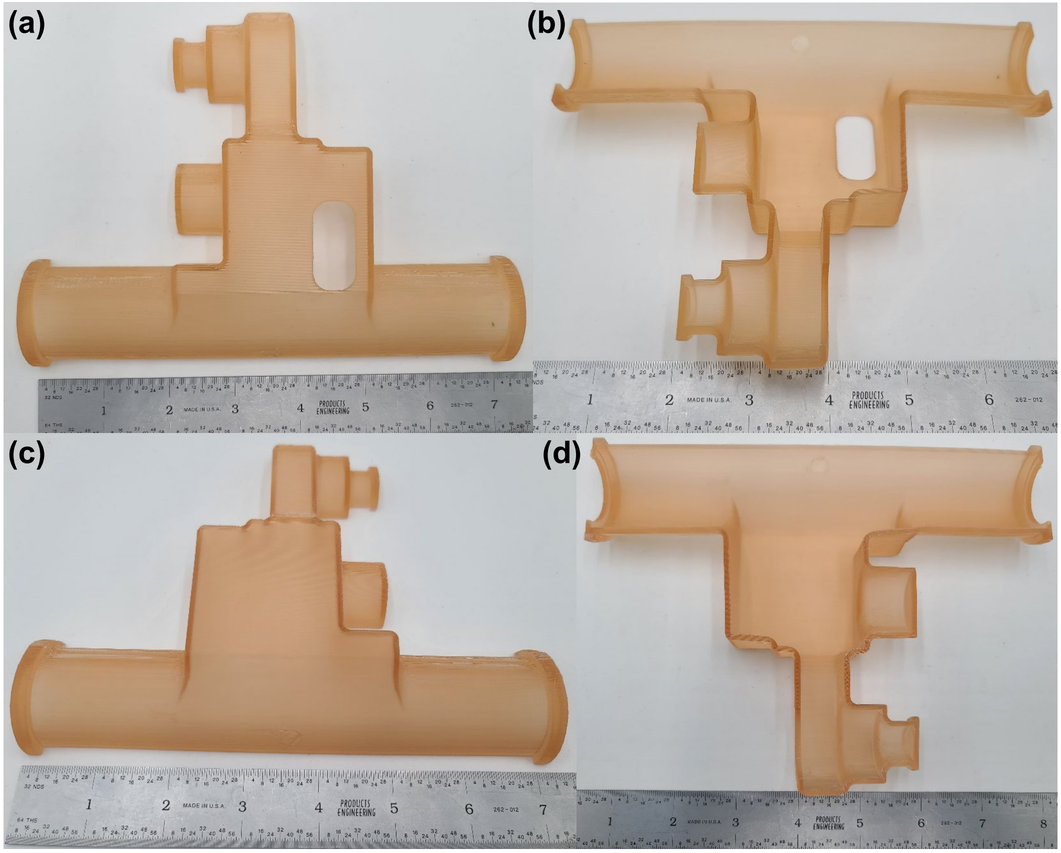

Figure 8. **Bus bar cover assembly subparts: (a) Part 1 top view, (b) Part 1 inside view, (c) Part 2 top view, and (d) Part 2 inside view.**

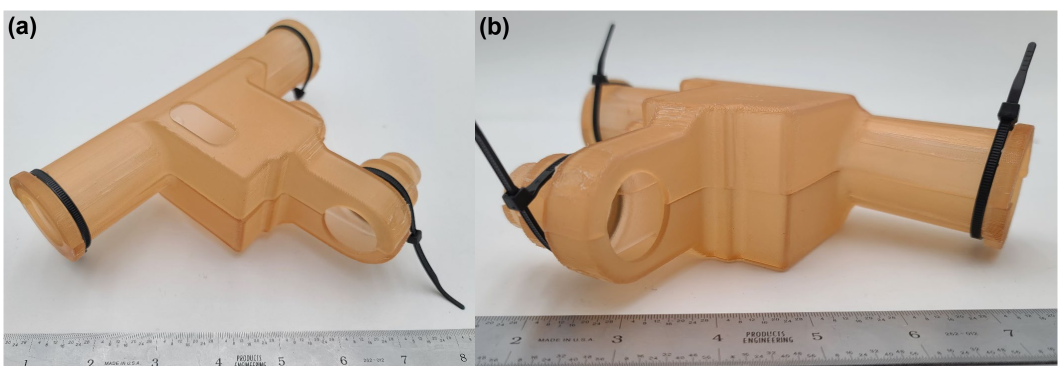

Figure 9. **Assembled bus bar cover assembly: (a) top view with Part 1 on top and (b) side view with Part 2 on top.**

Figure 10 shows the results of the fit test of the bus bar cover assembly. Figure 10a shows the location within the Bradley A4 fighting vehicle with Part 2 of the assembly removed showing the exposed electrical connections. The bolted joints where connections are made to the bus bar are misaligned, with the right connection coming towards the camera. Figure 10b shows the fit of the OEM (red) cover assembly, revealing a poor fit likely due to the misaligned electrical connections. Figure 10c compares the OEM part to the molded part fabricated using a 3D-printed dissolvable mold. The two objects appear similar, highlighting the viability of the sacrificial molding approach to produce parts with complex geometries from castable, thermosetting resins. Figure 10d shows Part 2 of the cover assembly installed with the OEM Part 1. Part 1 was wedged between other components and was too difficult to remove for this demonstration. The fit is qualitatively similar to the OEM fit. Neither provides a perfect seating of the cover onto the bus bar due to the misalignment of the electrical leads, which could be easily corrected by mechanical alignment of the electrical leads.

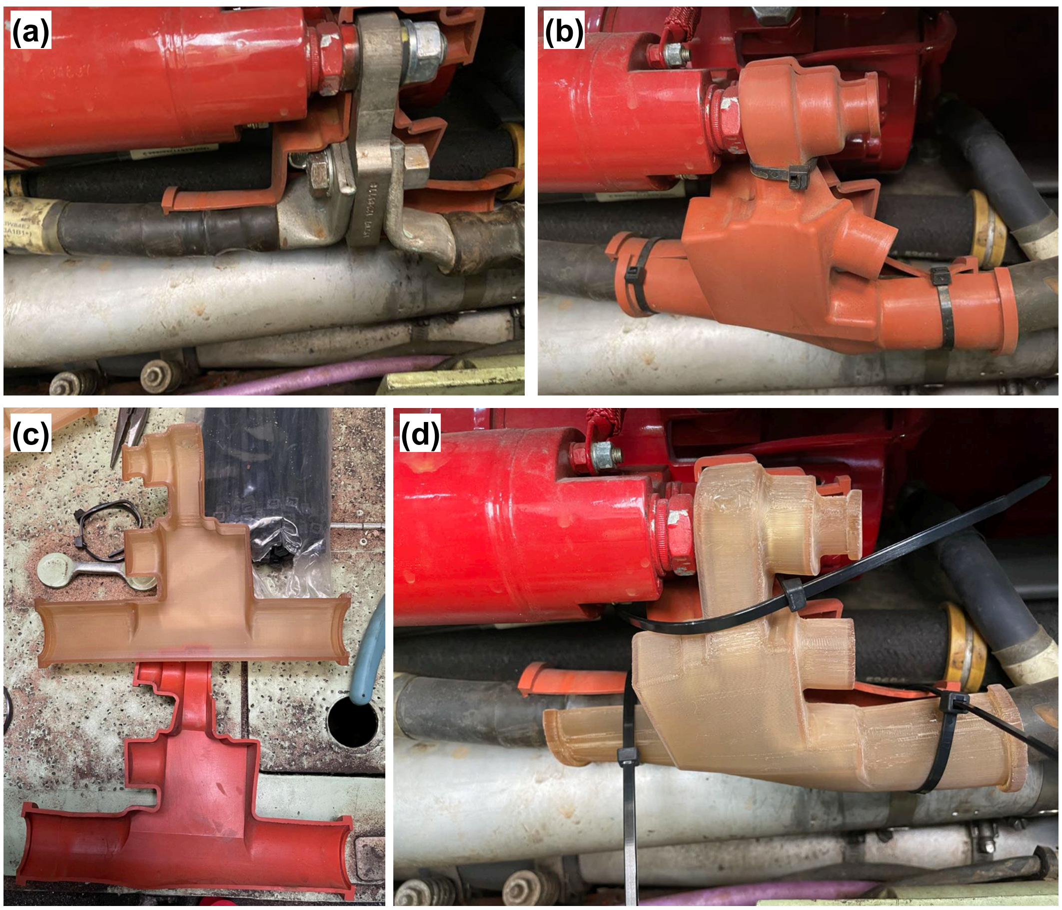

Figure 10. Bus bar cover assembly test fit in vehicle: (a) location of cover assembly in vehicle with OEM Part 2 removed, (b) fit of OEM assembled cover assembly, (c) side-by-side comparison of the OEM vs. the molded Part 2, and (d) molded Part 2 of the assembly installed on the vehicle.

3.3 Dimensional Accuracy of Fabricated Parts

The dimensional accuracy of the 3D-printed dissolvable mold approach is evaluated through a comparison to the intended dimensions in the CAD model. Measurements of the fabricated specimen are obtained using digital calipers to quantitatively compare to the CAD model. Several key features, labeled in Figure 11, of the fabricated samples are compiled in Table 1 along with their intended dimensions. The average deviation of all parts measured is 0.12 mm, which is similar to the resolution limit of the fused filament fabrication (FFF) process to make the molds.

Table 1. Comparison of the dimensions of the CAD vs. the fabricated part. (Lowercase letters in the left-hand column correspond to labels in Figure 11.)

	CAD dimension (mm)	Measured dimension (mm)	Absolute deviation (mm)
Part 1 of bus bar cover assembly			
Wall thickness (mm)	2.16	2.27	0.11
Hole height (mm)	31.75	31.86	0.11
Hole width (mm)	15.24	15.39	0.15
a	20.57	20.60	0.03
b	27.43	27.54	0.11
c	41.40	41.58	0.18
d	53.09	53.09	0.00
e	18.54	18.77	0.23
f	182.12	182.56	0.44
g	133.17	133.30	0.13
Part 2 of bus bar cover assembly			
Wall thickness (mm)	2.2	2.3	0.1
a	20.6	20.5	0.1
b	27.4	27.4	0.1
c	41.4	41.4	0.0
d	53.1	53.2	0.1
e	18.5	18.6	0.1
f	182.1	182.6	0.4
g	133.2	133.4	0.2
Resilient mount			
Wall thickness (mm)	10.04	10.03	0.01
Slit	1.02	1.08	0.06
a	91.95	91.90	0.05
b	70.10	70.04	0.06
c	15.88	15.97	0.09
d	50.04	49.93	0.11

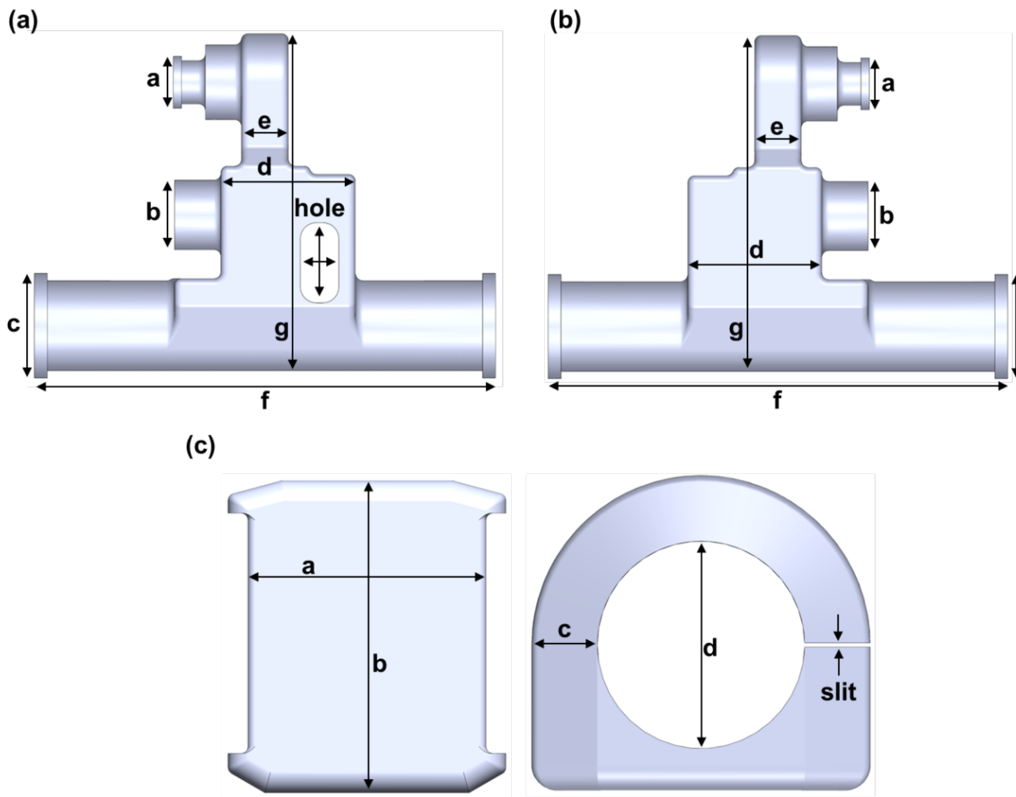

Figure 11. Labeled dimensions of the bus bar cover assembly reported in Table 1 for (a) Part 1 of the bus bar cover assembly, (b) Part 2 of the bus bar cover assembly, and (c) the resilient mount.

4. Discussion and Conclusions

Herein, various vehicle parts are readily fabricated using 3D-printable dissolvable molds to provide geometrically complex parts from materials not amenable to direct 3D printing. Careful mold design is employed to position the ports at locations on the part to allow air to escape, leading to fully dense parts. Further mold design considerations are necessary to avoid long bridges, which are very difficult to print via FFF, resulting in the 45° orientation of the part in the mold. Due to the high viscosity and short pot life of the urethane resins, a pressurized reservoir is employed to increase the rate of fill while a vacuum removes air bubbles. Further voids are removed by curing the casted part in a pressurized vessel to collapse any remaining bubbles. A fit test of both the bus bar cover assembly and resilient mount pieces shows similar performance to the OEM part. Overall, this approach provides a route to manufacture small batch and one-off parts that may otherwise be extremely costly and require long lead times.

5. References

1. Bischoff DJ, DeGrange MJ, Clay AM, Wetzel ED. Rapid, low-cost fabrication of reinforced, closed-loop toothed belts via 3D printed molds. DEVCOM Army Research Laboratory (US); 2025. Report No.: ARL-TN-1254.

2. Bischoff DJ, DeGrange MJ, Morales-Ferrer JM, Clay AM, Wetzel ED. 3D printed, dissolvable molds for the fabrication of geometrically complex, elastomeric energy absorbers. Mater Des. Submitted 2025 Oct.

List of Symbols, Abbreviations, and Acronyms

3D	Three-dimensional
ARL	Army Research Laboratory
BVOH	Butenediol Vinyl Alcohol
CAD	Computer-Aided Design
DEVCOM	U.S. Army Combat Capabilities Development Command
FFF	Fused Filament Fabrication
FMTV	Family of Medium Tactical Vehicles
GVSC	Ground Vehicle Systems Center
ID	Inner Diameter
NSN	National Stock Number
OD	Outer Diameter
OEM	Original Equipment Manufacturer

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