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Rapid Fabrication of an Electrically Insulating, Fiberglass Composite Wrench Using 3D-Printed Dissolvable Molds

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

NOTICES

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14. ABSTRACT
The use of 3D-printed tooling is demonstrated in the fabrication of an electrically insulating wrench for use on electrical lugs for Army generators. The tooling is used in a compression molding process to create a fiberglass composite wrench using high dielectric strength materials. A water-soluble thermoplastic filament, butenediol vinyl alcohol copolymer, is 3D printed using a standard desktop fused filament fabrication machine to produce the tooling. The use of a dissolvable filament simplifies the design by eliminating typical tool design considerations such as draft angles and undercuts. Part release is attained upon the dissolution of the mold in water, further simplifying the molding and de-molding processes while eliminating the need for mold release or ejector pins. A cost analysis is performed indicating that for part runs of less than 10 parts, the 3D-printed mold approach is approximately 10 times cheaper than conventional transfer molding and continues to show reduced cost for production runs of up to 144 parts. Furthermore, part lead times are dramatically reduced because a 3D-printed mold can be designed and produced in a few days, compared with lead times of months for conventionally machined metal transfer molds. This fabrication method is amenable to point-of-need manufacturing with relatively simple and low-cost equipment and materials.

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1. Introduction

The latest generation of electrical generators are the Advanced Medium Mobile Electrical Power Sources (AMMPS), which are replacing older models like the Tactical Quiet Generator (TQG). The AMMPS family of generators range from 5 to 60 kW to meet a range of mission requirements. Various models of the AMMPS (and/or TQG) generators, require different-sized "terminal nut wrenches" to interface with the terminal nuts contained in the output box of the generators.[1] The terminal nut wrench will be referred to as the wrench herein. Regardless of the exact size of the wrench head, the material used to manufacture the wrench must be as per technical drawing no. 88-20583,[2] which sets requirements for impact strength, electrical properties, stiffness, and temperature resistance. To achieve a national stock number (NSN) listing, this series of material property requirements must be met or exceeded. Despite the operator's manual[1] stating, "Ensure generator sets are shut down and output terminal board has no voltage prior to making any connections," maintaining electrical insulative properties in the wrench is critical for reducing the likelihood of injury if the wrench is used while the generator is energized.

The 30 kW AMMPS system, designated the MEP 1060, requires the wrench with part no. (PN) 88-21147,[3] which will be the primary demonstrator in this report. The CAD rendering of the wrench, with NSN 5120-01-375-4373, is shown in Figure 1. It is a CTM7883 anti-shock 43.6-mm (1.718-inch) 12-point box-type wrench designed to fasten a 28.6-mm (1.125-inch) nut. The wrench is stowed in a bracket on the inside of the output box door and is secured using rope that is connected to the wrench via the hole on the handle.

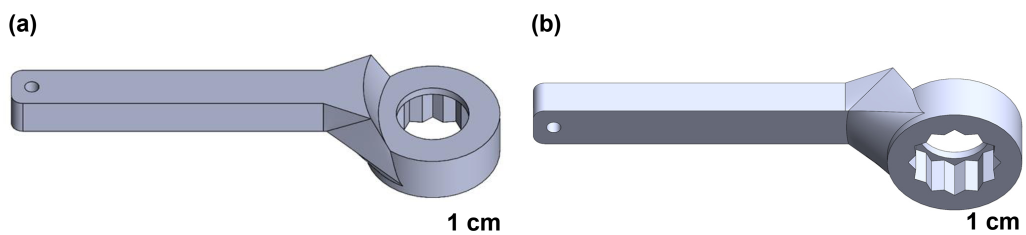


Figure 1. Electrically insulated wrench, CAD-generated preview.

Direct 3D printing a replacement wrench, as they become lost in the field or worn and damaged, is very challenging due to the limited material feedstock options for suitable electrically insulative materials that meet the 88-20583 requirements. Moreover, ordering the parts through the original equipment manufacturer (OEM) has proven difficult due to large minimum order quantities, long lead times, and high costs. To reduce lead times, cost, and logistics challenges, it is desirable to develop a manufacturing method that can be implemented at the point of need. Specifically, Army Battle Damage Assessment and Repair (guidelines allow for the expeditionary manufacturing and use of temporary replacement parts when conventional resupply cannot meet immediate Soldier needs. To combine the high performance of a castable thermosetting material with the geometric freedom of additive manufacturing (AM), 3D-printed, dissolvable molds can be employed. Sacrificial molds have been used to create a variety of Army-needed parts including energy-absorbing lattices,[4] replacement vehicle parts,[5] reinforced toothed belts used in unmanned aerial vehicles,[6] fully metal parts, and elastomeric parts with internally embedded hardware. The single-use, sacrificial molds can be used to mold parts from traditionally "unprintable" materials such as chopped glass fiber composites.

Herein, the wrench is fabricated from composite material composed of chopped fiberglass in an epoxy with high temperature resistance, high impact strength, and high dielectric strength. The fabrication process uses a 3D-printed mold (referred to as an "AM mold" throughout, particularly when contrasting relative to a conventional machined metal mold) made from butenediol vinyl alcohol copolymer (BVOH) that is water soluble, making part release easy and making any mold release compound unnecessary. Because the AM mold dissolves, mold design is greatly simplified without needing to consider draft angles, which would be important, for example, in the design of a transfer molding process. The AM mold consists of two parts: a female cavity into which the fibers are packed, and a male tool used to compact the material in a press.

2. Experimental

2.1 Materials

Chopped electrical-grade glass (E-glass) fibers with a 13-µm diameter, a 12.7-mm length, and a silane sizing were obtained from LBI Fiberglass (Groton, Connecticut). EpoxAcast 670 HT was obtained from Smooth-On (Macungie, Pennsylvania). This resin was selected because of its manufacturer-listed dielectric property ratings (Table 1), which meet or exceed the electrical requirements for the wrench application. Ultrafuse BVOH filament was obtained from BASF Forward AM (Heidelberg, Germany). Before printing, the filament was dried in an oven at 60 °C for at least 24 h. A medium-strength steel, grade 5, hex nut of size 1.125-inch × 7 threads per inch was obtained from McMaster-Carr (Elmhurst, Illinois). All materials were used as received.

Table 1. Comparison of the epoxy resin manufacturer-rated electrical performance with the Army requirements for the wrench.

Property	Requirement[2]	Rated performance[10]
Volume resistivity (ohm-cm) (ASTM D257)[7]	$>2 \times 10^{13}$	3.59×10^{15}
Dielectric constant (ASTM D150)[8]	>5	5.08
Dielectric strength (V/mil) (ASTM D149)[9]	>320	404

2.2 Mold Design and 3D Printing

2.2.1 Mold Design

The wrench was reconstructed from technical drawing 88-21147 using SolidWorks 2024 (Dassault Systems, Vélizy-Villacoublay, France). A mold for the wrench was designed in two parts, a female cavity and a male tool, that could be compacted on a press. To design the female tool, the wrench was subtracted from the top face of a 29.06- × 10.16- × 6.99-cm rectangular prism and an additional 1.52 cm of depth was added to the cavity. This added depth is necessary to enable all the fibers to be hand packed inside prior to compaction. The male tool was designed to protrude from the surface of a 29.06- × 10.16- × 0.64-cm rectangular prism by the same 1.52 cm amount. The shape of the extruded wrench on the male tool was shrunk by 0.8 mm on all vertical faces to allow the male tool to seat completely into the cavity upon closure. This gap was chosen not only for tolerancing between the two mold components, but also to provide a circumferential gap for excess resin to escape during compression.

Two iterations of the mold were necessary. The first iteration (Figure 2a) used a pin in the handle section inside the female cavity of 0.79 cm diameter. The pin length was equal to the final thickness of the wrench handle (2.13 cm), and the male feature that formed the open feature in the wrench head was equal to the final head thickness (2.77 cm). In the second iteration (Figure 2b), the pin feature had a fillet of 6.35 mm added and its height increased to 3.66 cm. The head feature was lengthened with a 3.96-cm cylinder extending up to 6.35 cm to eliminate the possibility of fibers being laid on that top surface. It is important to note that both the pin and the head cylinder features are still below the top surface of the male tool when the mold is completely closed. Pass-throughs for the pin and head in the male tool are present to reduce the amount of BVOH used.

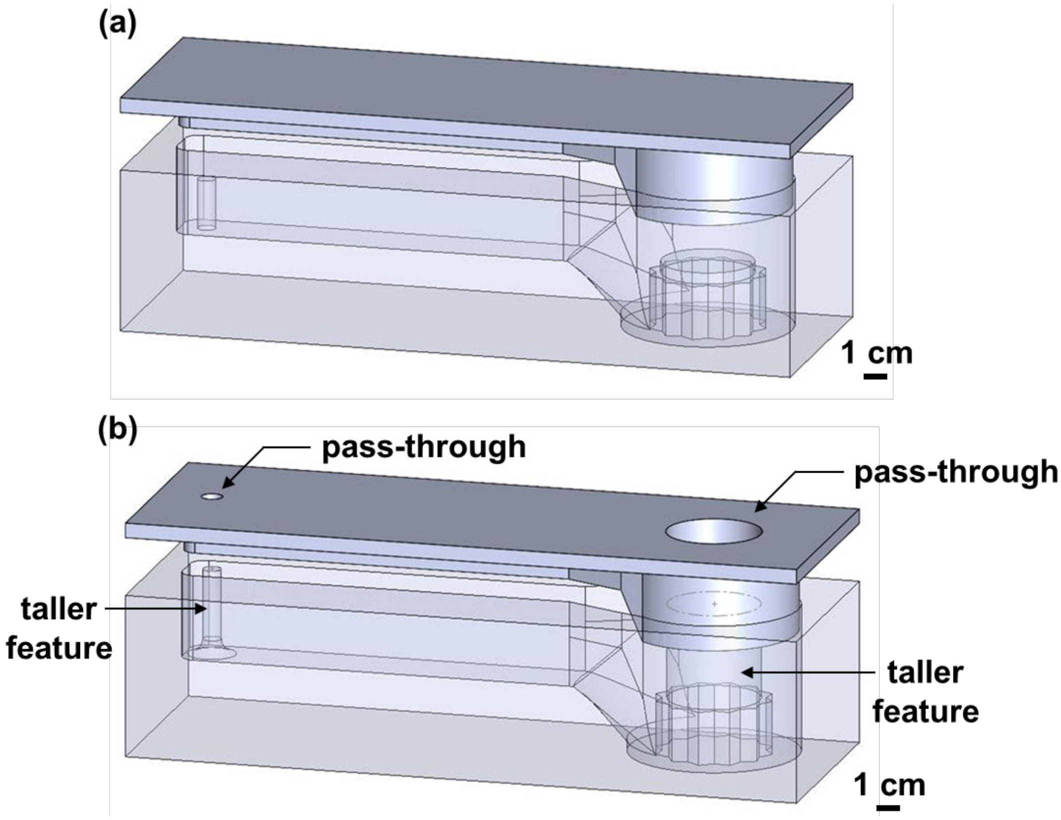


Figure 2. Two-part AM molds used to fabricate the wrench via compression molding: (a) first iteration and (b) second iteration.

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. In the second iteration, the number of perimeters was six. The parts used 20% rectilinear infill density because of its added compressive strength whereas gyroid infill would typically be used in a dissolvable mold because the large surface area enables rapid dissolution. 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. AM molds were 3D printed using 1.75-mm filament on a Prusa XL 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 65 °C to prevent the hygroscopic filament from absorbing moisture. Both parts were printed simultaneously on the same build platform that took 1 day and 22 h to finish using 725 g of BVOH. The first and second iteration of the molds are shown in Figures 3a and b, respectively. A final AM mold design is shown in Figure 4, identical to the second iteration mold but with the addition of an embossed U.S. Army Combat Capabilities Development Command (DEVCOM) logo.

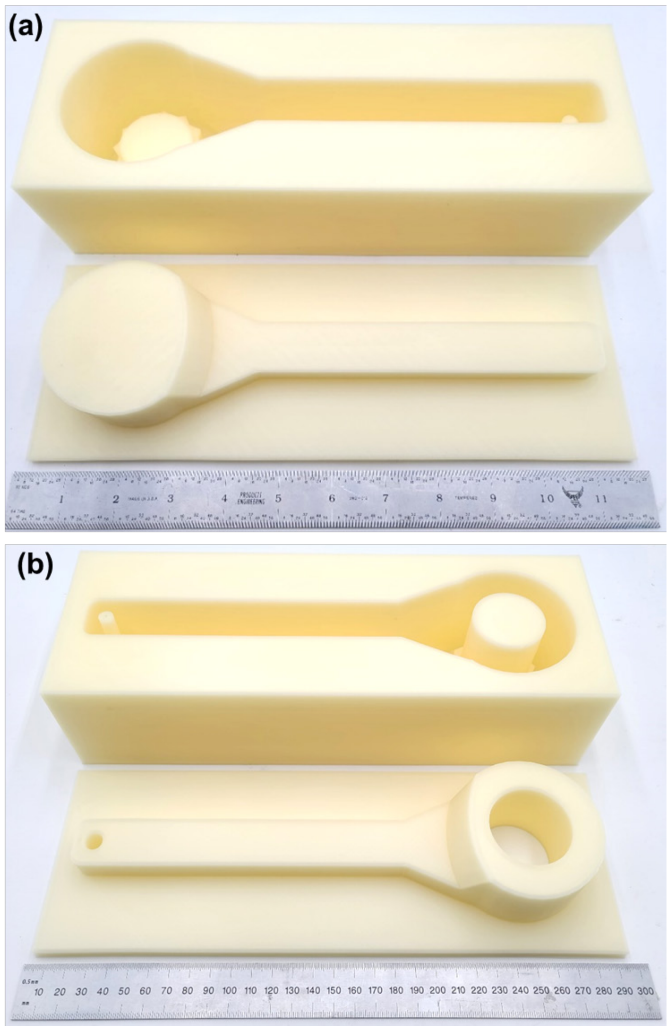


Figure 3. 3D-printed BVOH molds: (a) first iteration and (b) second iteration.

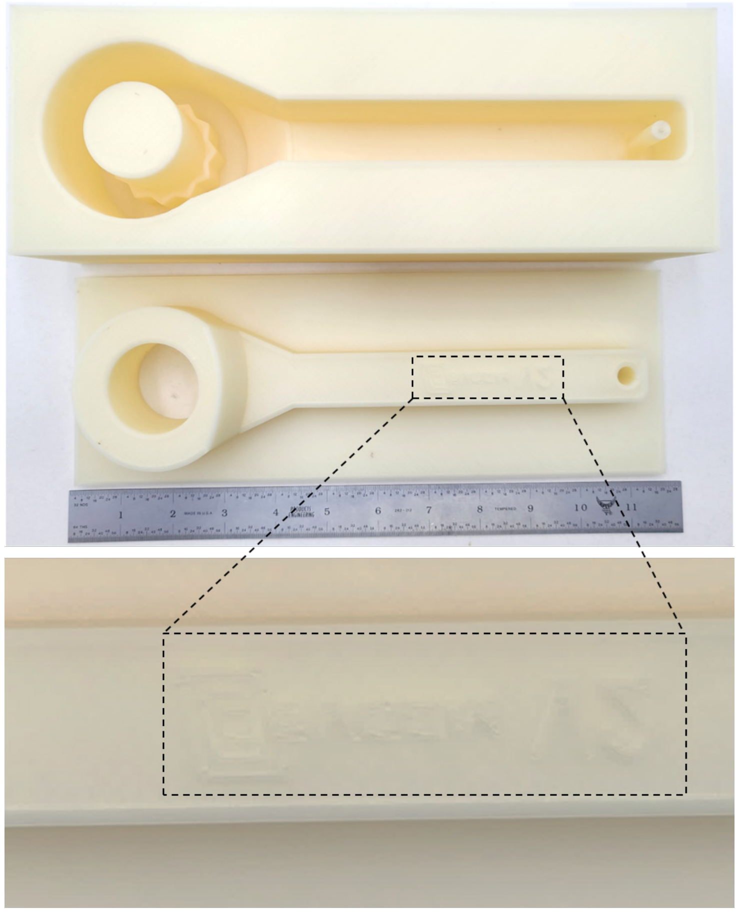


Figure 4. Final iteration of the BVOH mold containing the DEVCOM logo on the handle. The logo on the mold is mirrored to create the proper reflected image when debossed in the part.

2.3 Wrench Fabrication

The volume of the wrench, calculated using the CAD software, is 194.7 mL. Higher volume fractions of reinforcement enable higher part strength and stiffness, but also make mold filling, wetting, and compaction more difficult. To balance these considerations, 50 vol% fiber was the chosen composite formulation. A total of 247.3 g of the E-glass fibers (ρ = 2.54 g/mL) were weighed in a beaker (Figure 5a). To achieve a paste-like consistency of epoxy-wetted fibers that can be hand packed into the female tool, excess epoxy totaling 260% of the required 97.35 mL was prepared. In total, 291.1 g of epoxy (ρ = 1.15 g/mL) was prepared by combining 250.9 g of Part A and 40.2 g of Part B in a beaker. The surfaces of the molds were then coated with epoxy using a brush. The remaining epoxy was combined with the fibers and were hand mixed using a tongue depressor to avoid breaking the glass fibers until homogenous. The wetted fibers were then hand packed into the female tool ensuring that fibers were present in all teeth in the head and around the pin in the handle (Figure 5b). The male tool was then placed on top and seated into the cavity because the height of the packed fibers was below the top surface of the female tool. The mold was then placed under a shop press using a steel platen to distribute the force across the mold. The platens were covered with aluminum foil in anticipation of excess epoxy resin seeping out. The force of the press was gradually increased to 1 ton over the course of 1 h, allowing the material to flow and fill all space in the mold. Excess epoxy was readily observed flowing out of the gap between the two tools (Figure 5c). After the mold was fully closed, it remained under 1 ton of force for 24 h to permit the epoxy to cure. The mold was removed from the press and placed in an oven at 80 °C for 2 h followed by 150 °C for 3 h. The fully cured composite wrench mold was then submerged in a 14 L stirring bucket of water to release the part. Epoxy flashing was removed using a combination of cutting tools and sandpaper to achieve the final part.

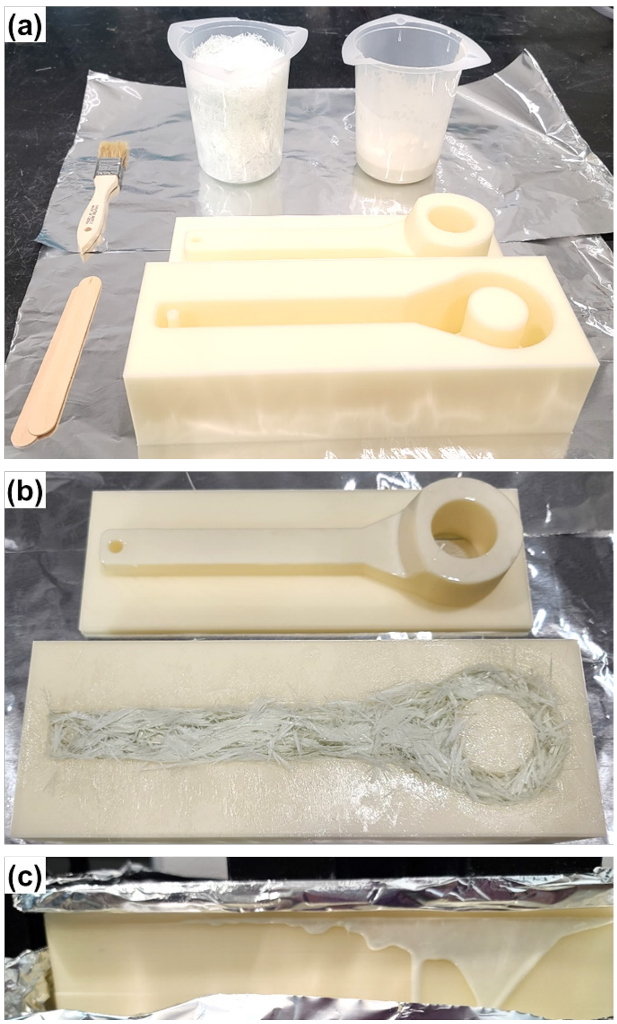


Figure 5. Fabrication of the wrench: (a) both mold parts along with pre-weighed fibers and mixed epoxy, (b) male tool with a coating of epoxy and the female tool hand packed with wetted fibers, and (c) fully closed mold with excess epoxy leaking from the interface between the mold pieces.

2.4 X-Ray Computed Tomography (XCT)

Computed tomography (CT) was performed using a ZEISS Xradia 620 micro-CT. The scan settings are detailed in Table 2. During scans, the wrench was fastened to the rotating stage with its longitudinal axis vertically aligned. When scanning the head of the wrench, the source was brought far from the sample and the detector was placed close to the sample to scan as much of the socket as possible. Because of the large resulting voxel size (55.3 µm), microporosity was not readily apparent, especially within the OEM sample. To better detect microporosity, an internal tomography of the handle of each wrench was scanned by bringing the source closer and the detector farther away, resulting in a voxel size of 9.92 µm. Dragonfly 3D World (version 2025) was used to segment the voids and calculate an estimated porosity.

Table 2. XCT scanning parameters.

Parameter	Wrench head	Wrench handle
X-ray voltage	80 kV	80 kV
X-ray power	10.5 W	10.5 W
X-ray current	125 µA	125 µA
Exposure time	8 s	3 s
Magnification	0.4×	0.4×
No. of projections	1601	1601
Binning	2	2
Source filter	air	air
Source to sample distance	213.68 mm	30.51 mm
Detector to sample distance	50.37 mm	179.61 mm
Voxel size	55.3 µm	9.92 µm

3. Results

3.1 Wrench Fabrication and Test Fit

The resulting wrench, fabricated via compression molding using the second iteration of the mold design, is shown in Figure 6. Importantly, there are no visible exposed glass fibers or void spaces on the exterior of the wrench. The detail in the head of the wrench, enabling the tool to be used on a hex nut, is captured. To prove that the wrench is geometrically accurate, a test fit with a 28.6-mm (1.125-inch) hex nut is shown in Figure 7. The test fit shows that the nut fits with only a small amount of tolerance, intended by design, to allow the wrench to be easily applied or removed from the nut. The fit is excellent, helping to avoid the rounding of the teeth over time with repeated use. Figure 8 shows a second wrench, fabricated with the additional DEVCOM logo feature. Again, the feature resolution is excellent.

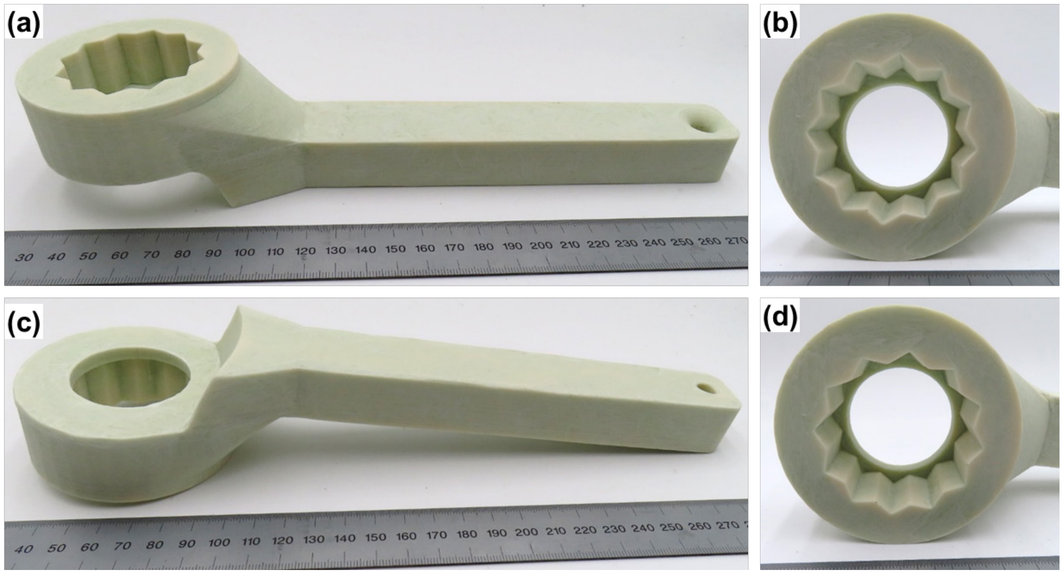


Figure 6. Fabricated electrically insulating wrench: (a) bottom view, (b) head, (c) top view, and (d) head.

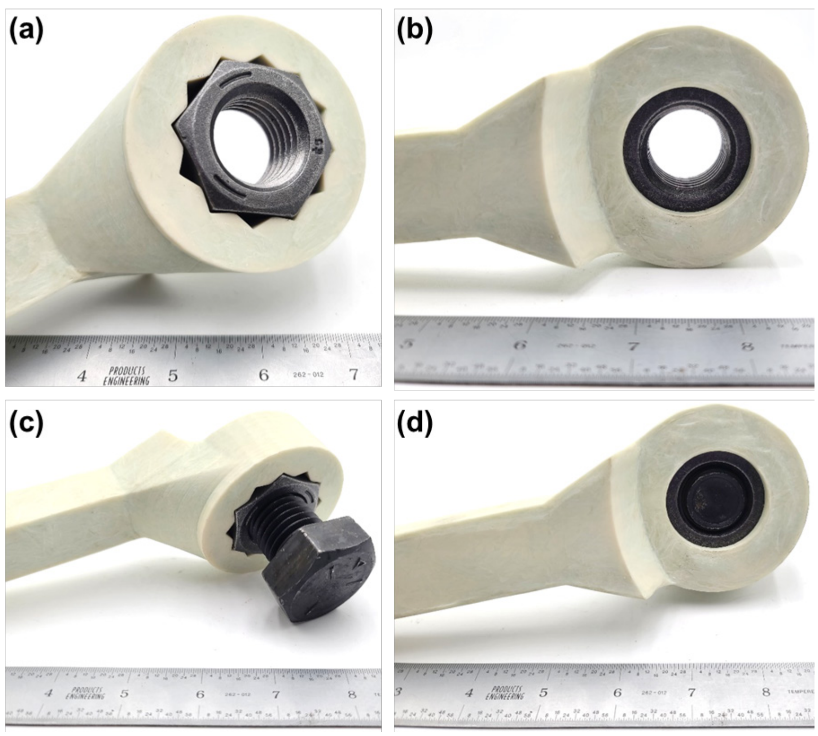


Figure 7. Fit test with a 28.6-mm (1.125-inch) hex nut: (a) hex nut inserted into wrench head, front view, (b) hex nut inserted into wrench head, rear view, (c) hex nut installation onto bolt, front view, and (d) hex nut installation onto bolt, rear view.

Figure 8. Fabricated electrically insulating wrench with DEVCOM logo on the handle.

3.2 Visual Comparison to OEM Part

A comparison between the AM molded wrench and OEM wrench is shown in Figure 9. In Figure 9a, ejector pin marks are readily observed on the surface of the OEM wrench. The ejector pins, marked by black arrows, are a surface defect derived from the transfer molding manufacturing process where a high force is used on the pins to forcefully eject the wrench from the metal mold where the compression took place. Another difference seen in Figure 9b is the marking applied to the handle that describes the CAGE number (30554) of the manufacturer and the PN (88-21147). The second iteration AM mold was originally designed without a marking, yet due to the ease of making a change in the digital design, a subsequent marked version was readily produced at negligible added cost.

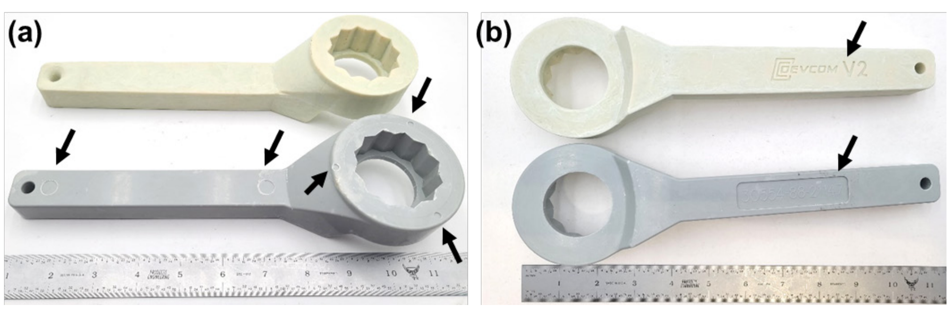


Figure 9. Comparison of AM molded part (top) to OEM part (bottom): (a) view with head facing up and (b) view with head facing down.

3.3 XCT Results

3.3.1 General Characteristics of the Wrenches

XCT results shown in Figure 10 compare the internal features of both the OEM and AM molded wrench (see Figure 9). All CT images illustrate the wrenches oriented vertically with the head (Figures 10a and d) on top. Bulk internal tomographies of the handle (Figures 10b and e) are also vertically orientated. A single top-down slice of each handle is also illustrated (Figures 10c and f). In the OEM handle, there is a crack (Figure 10b, c) observed that could be either a manufacturing defect or damage from use. The crack may not be representative of the whole wrench, but rather just the portion that was scanned. The glass fibers in the AM molded wrench (Figures 10e and f) are more visually apparent compared with those in the OEM wrench. This difference could be due to the individual fibers in the AM molded wrench still being closely associated as a multi-fiber tow, whereas the OEM wrench fibers may have been more vigorously compounded and dispersed prior to molding. The orientation of the fibers in the AM molded wrench appears to be more aligned compared with the OEM wrench. Figure 11 shows the location and orientation of XCT scans shown in Figure 10.

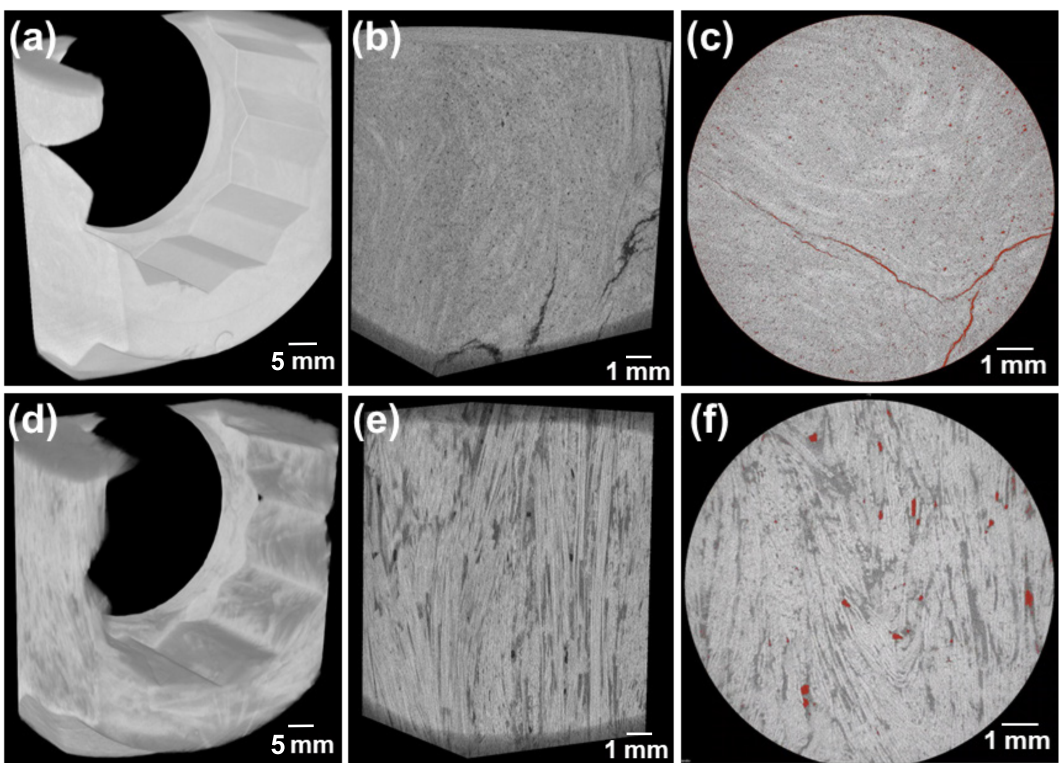


Figure 10. XCT comparison of fabricated wrench to the OEM part. OEM wrench (a) head, (b) handle, and (c) handle with voids highlighted in red. AM molded wrench (d) head, (e) handle, and (f) handle with voids highlighted in red.

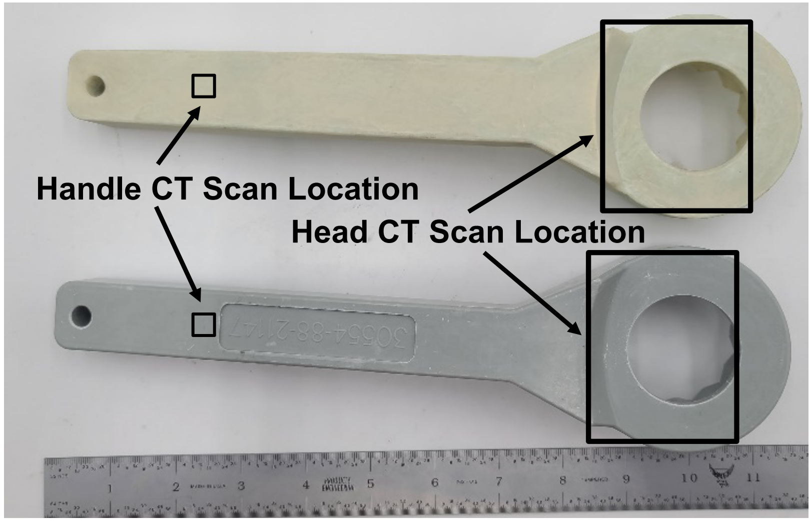


Figure 11. Location and orientation of XCT scans shown in Figure 10.

3.3.2 Determination of Void Fraction

The scan of the OEM wrench reveals numerous small (on the order of 34-μm diameter or less) pores in Figure 10a. Generally, the average size of pores in the OEM wrench are smaller than the pores in the AM molded wrench in Figure 10d (on the order of 110-μm diameter); however, there are a larger number of pores in the OEM wrench. For each slice in the scan, a porosity percentage was calculated for that area and an average across all slices was used to compare the two wrenches. The average porosity across all slices was 1.91% for the OEM wrench and 0.52% for the AM molded wrench. Porosity can be introduced into the part in various ways including trapping air, shrinkage during cooling and curing, trapping volatiles from the curing reaction, and poor mold design. In comparison with a typical part directly 3D printed with 100% infill density, which typically leaves a porosity of 4% or more,[11] both of the wrenches analyzed herein perform better and are generally considered low porosity.

3.4 Cost Analysis

The OEM wrench is manufactured using a transfer molding process. In this process, a predetermined volume of molding compound is added to a preheated transfer pot. Once at temperature, a ram compresses the compound through a sprue into the heated, closed mold cavity. The compound remains in the heated mold under pressure until the thermosetting polymer is sufficiently solidified or cured, at which time it is ejected. The transfer molding process is appropriate for large volume manufacturing of the same item.

The 3D-printed, dissolvable AM mold approach is well suited for the manufacture of one-offs and small batches of high-value Army parts. The high value can be derived from an immediate need for the part in the field, difficulty of procuring the part from the OEM, or requirements for custom materials or geometry. Table 3 lists the raw material costs for materials purchased at the laboratory scale. The BVOH filament cost is listed at $100/kg, based on a recent quote from a material vendor, although the filament used in the present study was purchased at $160/kg. The table also lists the costs required for each material to manufacture a single wrench, revealing that BVOH filament is the most expensive component. The next most significant cost is the high-temperature epoxy that makes up 50 vol% of the part. During manufacturing, an excess amount of epoxy is used, allowing squeeze out from the mold during the compression molding step to ensure that the entire mold volume is completely filled with material. The cost of the glass fiber and water are not significant. The total material cost per AM molded wrench is $82. As the quantity of materials ordered for scale-up increases, the absolute cost per kilogram of each material will decrease.

Table 3. Material feedstock costs and quantity needed to manufacture a single wrench using the AM mold process.

Material	Purchased quantity (kg)	Cost per weight ($/kg)	Mass required per wrench (kg)	Cost per wrench ($)
BVOH filament	0.75	100.00	0.7	70.00
EpoxAcast 670 HT	5.26	36.00	0.29	10.44
1/2-inch chopped E-glass	18.14	6.70	0.25	1.68
Water	NA	0.00	14	0.04
			Total	82.16

In comparison, one choice for a transfer resin that meets the technical drawing no. 88-20583 requirements is the Syensqo FM-8130 12.7-mm glass roving reinforced phenolic molding compound. The estimated cost per wrench for this material is $86 using a recent quote for the resin. Therefore, the materials cost for the AM mold approach is comparable to the cost of traditional transfer molding.

Table 4 summarizes the process time and labor hours required for each step in the manufacturing process for the AM molded part. The table includes estimates for building a single wrench, and for producing 10 wrenches in parallel. With the exception of casting and flash removal, which must be done on a unit-by-unit basis, all other steps can be parallelized to reduce the effective time per wrench. Parallelization can be achieved using a print farm to make several molds simultaneously by curing several wrenches together in a large oven, and by using a larger tank of water to dissolve several molds at once. By producing 10 wrenches in parallel, the total time required to produce 1 wrench is decreased by an approximate factor of 8 while the number of labor hours is decreased from 2.3 to 2.1 per wrench. The difference in manual labor hours involved in transferring the AM mold to either an oven or a dissolution tank for 1 versus 10 wrenches is expected to be negligible. The number of labor hours required to configure 10 3D printers is less in the 10-wrench case as the model needs to be sliced only once. The machine set-up time is dominated by loading the BVOH filament into the dry box and loading the material into the printer.

Table 4. Manufacturing process duration and labor hours to build the wrench(s) using the AM mold.

	1 wrench		10 wrenches	
Manufacturing step	**Process time** (h)	**Labor** (h)	**Process time** (h)	**Labor** (h)
3D printing	48	0.1	48	0.5
Casting	1.5	1.5	15	15
Curing	27	0.1	27	0.1
Mold dissolution	5	0.1	5	0.1
Flashing removal	0.5	0.5	5	5
Total	82	2.3	100	20.7
Total, per wrench	82	2.3	10	2.1

The transfer molding process requires an expensive heated hydraulic press and mold. The up-front cost of a press is estimated at $100,000. The machined metal mold required to produce a specific part, such as this wrench, costs on the order of $10,000 and requires a lead time of 2 to 6 months to produce. An estimate of the equipment costs associated with this process to produce the first wrench from both the transfer molding and AM molding processes are shown in Table 5. Considerably less cost is required to start up the 3D-printed molding process.

Table 5. Startup equipment costs to produce a wrench.

Transfer molding (OEM process)		AM mold	
Equipment/ supplies/ labor	**Estimated cost** ($)	**Equipment/ supplies/ labor**	**Estimated cost** ($)
Heated hydraulic press	100,000	3D printer	1,000
Machined metal mold	10,000	Dry box	100
		Shop press	100
		Oven	1,000
		Dissolution tank	100
		Flash removal tools	100
Total cost	110,000		2,400

The tradeoffs between the transfer molding and AM molding processes are sensitive to the number of parts required, *N*. The overall cost of an operation can be estimated as

$$Total\ cost = Fixed\ costs + (N \times Cost\ per\ unit) \tag{1}$$

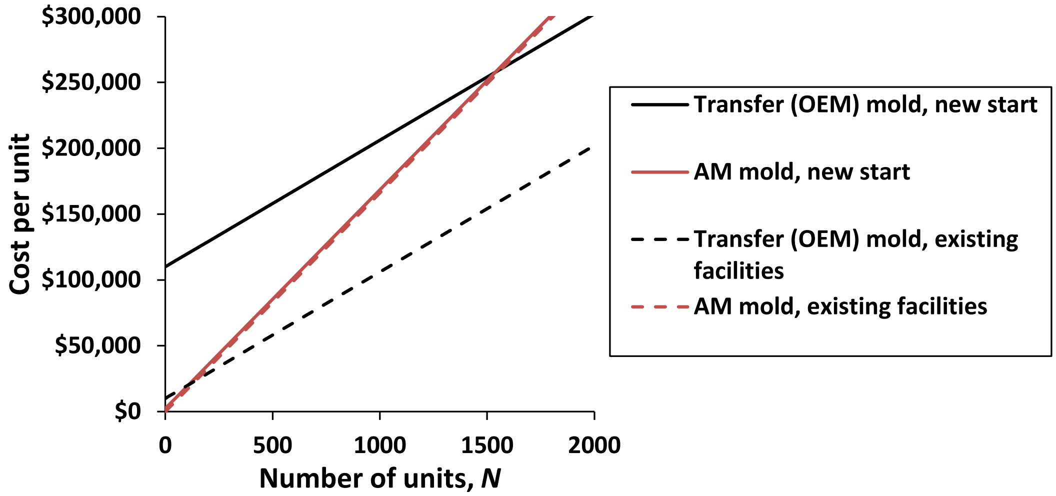
Material costs per unit were estimated previously (see Table 3) as $82/unit and $86/unit for AM molded and transfer molded, respectively. Labor per unit was previously estimated at 2.1 h per wrench (see Table 4) for a parallel production process of 10 wrenches per batch. For transfer molding, a fixed labor cost of 1 h for die setup and then 0.25 h per unit during production is used for calculations. A labor rate of $40/h is assumed.

Two production scenarios are considered. The first scenario, "startup," requires purchasing all equipment as fixed costs. For the AM molding technique, we estimate startup fixed costs (see Table 5) to be $2,400, compared to $110,000 for the transfer molding process. The second scenario assumes that all production equipment (3D printers, transfer press, oven, etc.) already exists in a fabrication facility, so that the only fixed equipment cost is the cost of a custom die for the wrench.

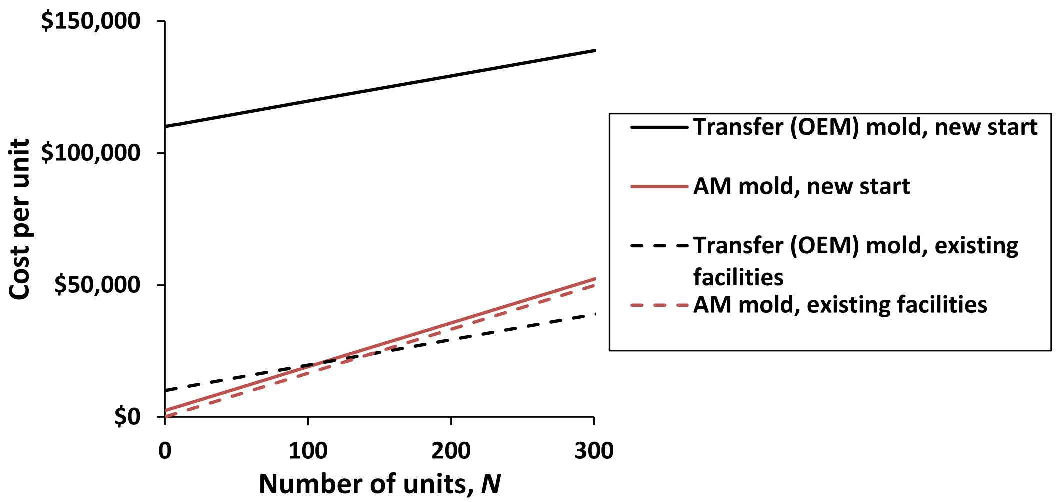
Table 6 and Figure 12 compare total production run costs as a function of number of units. For the startup scenario, the cost for transfer molding is dramatically higher compared with AM molds. Under these assumptions, the transfer molding process only becomes less expensive than the AM molding process for production runs of 1538 units or higher. If we instead assume that the major equipment is preexisting, and only the transfer die for the wrench needs to be purchased, then the total production cost is lower for the AM mold process for 144 or fewer parts.

Table 6. Cost to produce a wrench as a function of number of units produced, for startup conditions where all equipment must be purchased, and for the case where equipment and facilities already exist. Labor cost is assumed to be $40/h.

	Startup				Existing facilities			
	Transfer (OEM) mold		AM mold		Transfer (OEM) mold		AM mold	
Fixed costs ($)	110,000		2400		10,000		0	
Fixed labor (h)	1		0		1		0	
Material per unit ($)	86		82		86		82	
Labor per unit (h)	0.25		2.1		0.25		2.1	
N	**Total cost ($)**	**Cost per unit ($)**	**Total cost ($)**	**Cost per unit ($)**	**Total cost ($)**	**Cost per unit ($)**	**Total cost ($)**	**Cost per unit ($)**
1	110,136	110,136	2,566	2,566	10,136	10,136	166	166
2	110,232	55,116	2,732	1,366	10,232	5,116	332	166
5	110,520	22,104	3,230	646	10,520	2,104	830	166
10	111,000	11,100	4,060	406	11,000	1,100	1,660	166
20	111,960	5,598	5,720	286	11,960	598	3,320	166
50	114,840	2,297	10,700	214	14,840	297	8,300	166
100	119,640	1,196	19,000	190	19,640	196	16,600	166
200	129,240	646	35,600	178	29,240	146	33,200	166
500	158,040	316	85,400	171	58,040	116	83,000	166
1000	206,040	206	168,400	168	106,040	106	166,000	166
2000	302,040	151	334,400	167	202,040	$101	332,000	166



(a)



(b)

Figure 12. Estimated cost per unit for transfer molding and AM molding, for startup conditions where all equipment must be purchased, and for the case where equipment and facilities already exist: (a) consideration up to 2000 units and (b) consideration up to 300 units.

4. Discussion and Conclusions

The 3D-printed, dissolvable mold approach provides several advantages compared with legacy manufacturing approaches. First, the lead times are dramatically shorter. A lead time of roughly 1 week is needed to design a mold, print the mold, cast and cure the composite, and then dissolve the mold. In contrast, a traditional metal tool takes months to fabricate. Furthermore, because of the short lead time for the AM mold, it is possible to iterate on mold design to optimize product quality.

In contrast, if a machined metal tool has a deficiency, it takes months to undertake each subsequent design improvement.

The second demonstrated advantage of the AM molding technique is dramatically reduced costs. For production runs of 10 parts or less, the AM molding technique is roughly 10 times cheaper than transfer molding, even if the only custom equipment expenditure is for the metal die. Up to 50 parts, under the same conditions, the AM molding method is still approximately half the cost per unit compared with using a transfer mold.

Furthermore, the use of 3D-printed molds dramatically expands the options for customizability. There are at least two variants (head sizes) for this lug wrench application, e.g., PN 88-21147 versus 88-21148. For the AM molds, there is negligible additional cost or lead time to produce two wrench designs. In contrast, each new transfer mold requires roughly $10,000 and months of lead time. In the present study, the addition of a DEVCOM logo to the last mold design is a good example of how quick and easy it is to update a part design using a 3D-printed mold.

For the wrench application in particular, the visual appearance and mechanical feel of the wrench are comparable to, or better than, the OEM wrench. The fit test of the wrench using a 1.125-inch hex nut confirms its functionality. Porosity measurements using XCT show that the density of the part molded in AM tooling is superior to that of an exemplar wrench produced using transfer molding.

This technology is compatible with point-of-need manufacturing demands and can be performed within an expeditionary environment, such as the Army's Metal Working and Machine Shop Set. These units are mobile, self-contained fabrication facilities designed to be rapidly deployed to the field with military units to provide advanced manufacturing, repair, and diagnostic capabilities. Using an FFF-based 3D printer is straightforward, requiring minimal training (<1 h) for Soldiers to get up and running. Minimal training (<1 h) would be required to explain other parts in the process including mixing of the resin, packing the fibers, and using the shop press.

Future work for improving the 3D-printed tooling described herein includes reducing BVOH use via multimaterial printing to both reduce material costs and dissolution time. The design of the wrench mold can be altered to adopt a vacuum infusion of resin around the fibers, streamlining the process to reduce the amount of manual labor required. To assist the Army in adopting such an expeditionary manufacturing approach, the process should be added into the Army's digital repository, and a protocol should be developed to enable the expeditionary casting of high-performance composites into dissolvable molds.

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List of Symbols, Abbreviations, and Acronyms

3D	Three-Dimensional
AM	Additive Manufacturing
AMMP	Advanced Medium Mobile Electrical Power Sources
ARL	Army Research Laboratory
BVOH	Butenediol Vinyl Alcohol Copolymer
CAD	Computer-Aided Design
CT	Computed Tomography
DEVCOM	U.S. Army Combat Capabilities Development Command
FFF	Fused Filament Fabrication
NA	Not Applicable
NSN	National Stock Number
OEM	Original Equipment Manufacturer
PN	Part No.
TQG	Tactical Quiet Generator
XCT	X-ray Computed Tomography

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