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Rapid, Low-Cost Fabrication of Reinforced, Closed-Loop Toothed Belts via 3D Printed Molds

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

NOTICES

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14. ABSTRACT
3D printed molds are used to fabricate custom length, fiber-reinforced, closed-loop toothed belts. Two strategies are demonstrated to release the cast belt: dissolution of a mold 3D printed using a water-soluble butenediol vinyl alcohol copolymer (BVOH) polymer, and mechanical removal of a 3D printed, conventional polylactic acid mold. The results show that belts with excellent geometric precision can be produced using either technique; however, the BVOH molds produce a higher-quality belt with easier part release. Belts produced using fiberglass reinforcement and an 80A durometer, two-part castable urethane were tested in tension and found to produce tensile strength and stiffness that are likely to be sufficient for short-term use in many Army applications.

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1. Introduction

Toothed belts are flexible belts with teeth molded on the inside designed to mate with toothed pulleys or sprockets. The teeth, which increase the surface area in contact with the sprocket, prevent the belt from slipping and are used to transfer torque and precise motion for indexing or timing purposes. The belts are composed of two parts: 1) the soft, flexible teeth and matrix and 2) the strong, internal reinforcing fibers. The matrix material encases the fibers and provides the teeth with some flexibility to properly mate with the sprockets. The matrix is typically made from rubber such as neoprene, vulcanized rubber, hydrogenated nitrile rubber, or thermoplastic polyurethane (TPU) with a durometer of approximately 80A. The reinforcement is a fabric, weave, belt, or lattice, and can be composed of steel, nylon, aramids, glass, carbon fiber, or other materials depending on the application and forces required. The reinforcement provides longitudinal stiffness to the belt to prevent stretching that could lead to tooth slip, lash, or lag during force transmission.

The reinforced belts find several Army applications in vehicles, robotics, drones, and motion control systems including 3D printers. For example, flight control surfaces in some unmanned aerial vehicle designs are driven by toothed belts coupled to the sprocket on a servomotor. The DoD has a demand for point-of-need manufacturing of customer toothed belts. Soldiers are often located in remote or austere environments where resupply via conventional logistics can be challenging. For example, if a critical belt breaks, it might take weeks or months for a replacement part to be delivered. Alternatively, 3D printing can be used to produce replacement parts quickly and cheaply. It is possible to create a toothed belt directly by 3D printing TPU; however, these conventional TPUs are unreinforced, resulting in a belt with low stiffness and high stretch. These belts are likely to slip under low loads and are generally unsuitable for most applications. Therefore, it is necessary to develop a methodology to efficiently produce custom length, high-stiffness toothed belts.

Herein, 3D printing is used to create a mold through which these toothed belts are produced to any diameter (length), width, and thickness. The manufacturing process is evaluated using two types of 3D printed mold material: a water-soluble thermoplastic, in which the cast belt is released via mold dissolution; and a structural thermoplastic, which requires mechanical destruction of the mold. The molds can be designed to fabricate several belts simultaneously, reducing the effective per-belt manufacturing time.

2. Experimental

2.1 Materials

Ultrafuse butenediol vinyl alcohol copolymer (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. Polylactic acid (PLA) filament was obtained from Prusa Research (Prague, Czech Republic). The urethane PMC 780 DRY (80A, $E_{100\%}$ = 2.76 MPa, ε_b = 750%) was obtained from Smooth-On, Inc. (Macungie, Pennsylvania). The reinforcement (Phifer BetterVue screen, model no. 3027671) is a woven-fiberglass-reinforced polyester screen that is readily available at home improvement stores. This screen material has a pitch of 1.4 mm, wire diameter of 0.3 mm, effective thickness of 0.31 mm, and areal density of 115 g/m^2. The screen material is most likely fiberglass with a thermoplastic coating. A benchmark, commercial timing belt (Gates Power Grip GT LL-2GT RF) from Prusa Research (Prague, Czech Republic), used in the kinematics system of their i3 3D printers, was used to compare with the fabricated belts. The pitch of the teeth is 2 mm and width is 6 mm. This commercial belt has fiberglass reinforcement, neoprene backing, neoprene teeth, and nylon facing.

2.2 Mold Design and 3D Printing

The dimensions of the desired belt are shown in Figure 1. The belt has 50 teeth and a pitch of 2.8 mm for an overall length of 140 mm. The rounded teeth, designed to mate onto a servo-driven sprocket, have a curvature diameter of 1.35 mm. Not including the teeth, the thickness of the belt is 0.65 mm and the width is 4 mm.

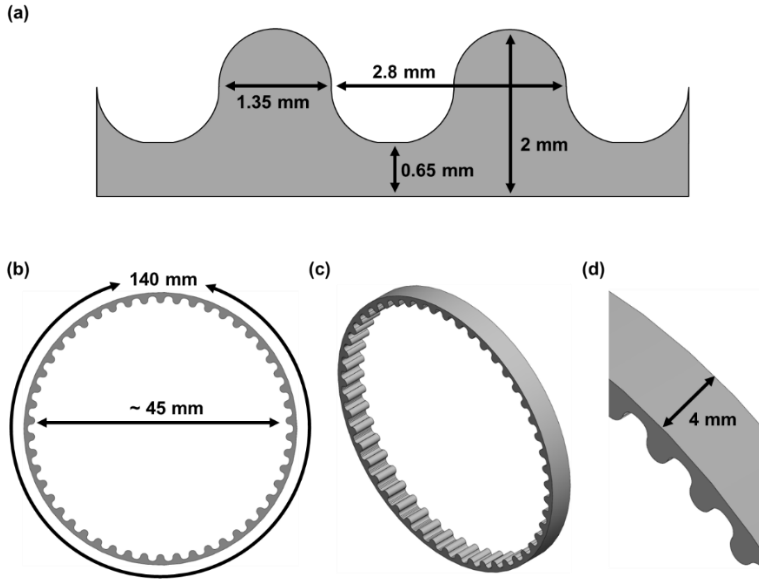


Figure 1. **(a) Dimensions of the teeth, thickness, and tooth separation, (b) front view of the toothed belt, (c) angled view of the toothed belt, and (d) dimension of the belt width.**

Two mold geometries were fabricated and evaluated: a single belt mold (Figure 2) and mold for fabricating five belts in parallel (Figure 3).

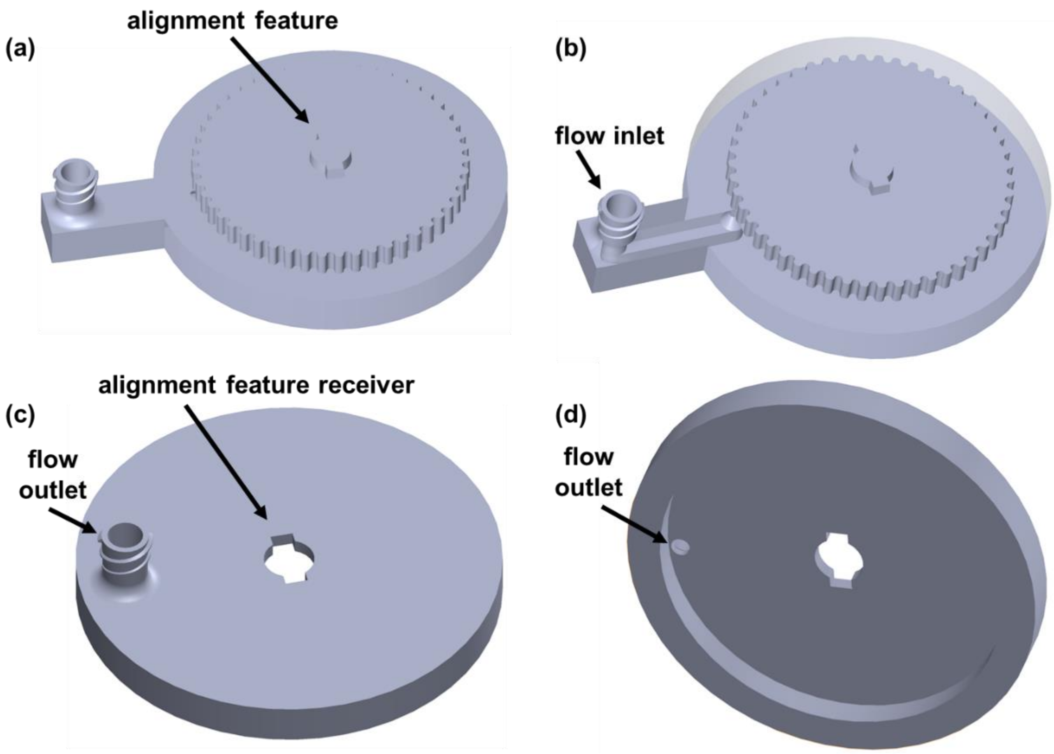


Figure 2. **(a) Part A of the single-belt mold, (b) partial transparent view of part A displaying the routing of resin from the Luer lock connection to the belt, (c) top view of part B of the single-belt mold, and (d) bottom view of part B of the single-belt mold.**

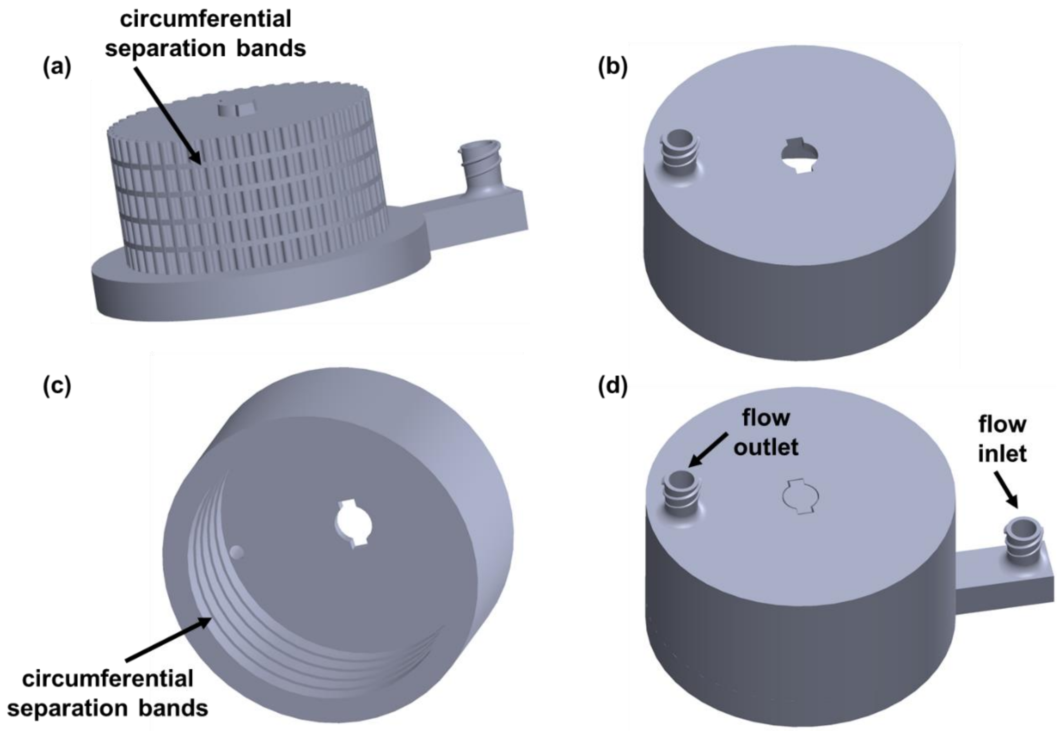


Figure 3. (a) Part A of the five-belt mold, (b) top view of part B of the five-belt mold, (c) bottom view of part B of the five-belt mold, and (d) assembled view of parts A and B.

The belt molds are split into two pieces, parts A and B. Part A includes an alignment feature on the top that seats into a receiver in part B; a Luer lock fitting designed to receive a syringe containing the polymer resin; and a toothed center cylinder to create the tooth features on the belt. Part B acts as a lid placed on top of part A with alignment enforced via the alignment feature and receiver. The top features a Luer lock that connects to a vacuum source. When part B is assembled onto part A, there is a 2.9-mm annular gap between the cylindrical walls where the reinforcement is added.

For the mold designed to create five belts (Figure 3), parts A and B of the mold also include 1-mm-wide protruding circumferential separation bands on the inner mold walls used to differentiate the individual belts. These features leave behind a recessed circumferential band on the casted part that serves as a guide for cutting the molded part into individual belts.

Molds were 3D printed using 1.75-mm filament on a MK4 (Prusa Research) (Prague, Czech Republic) equipped with a 0.4-mm brass nozzle using 15% gyroid infill density. Single-belt molds were printed using BVOH; five-belt molds were printed using BVOH and PLA (Figure 4). The print temperatures for BVOH were 225 °C for the nozzle and 60 °C for the bed. For PLA, the print temperatures were 215 °C for the nozzle and 60 °C for the bed. Other printing parameters used were taken from the default print profile in the slicer software (Prusa Slicer) for 0.2-mm-layer height. Typical speeds are approximately 100 mm/s for print moves, and the extrusion width is 0.45 mm. The number of perimeters was increased to 3 and 1-mm top and bottom surfaces were added. Part B was printed using rectilinear supports and oriented such that support material would not need to be removed from the male Luer lock.

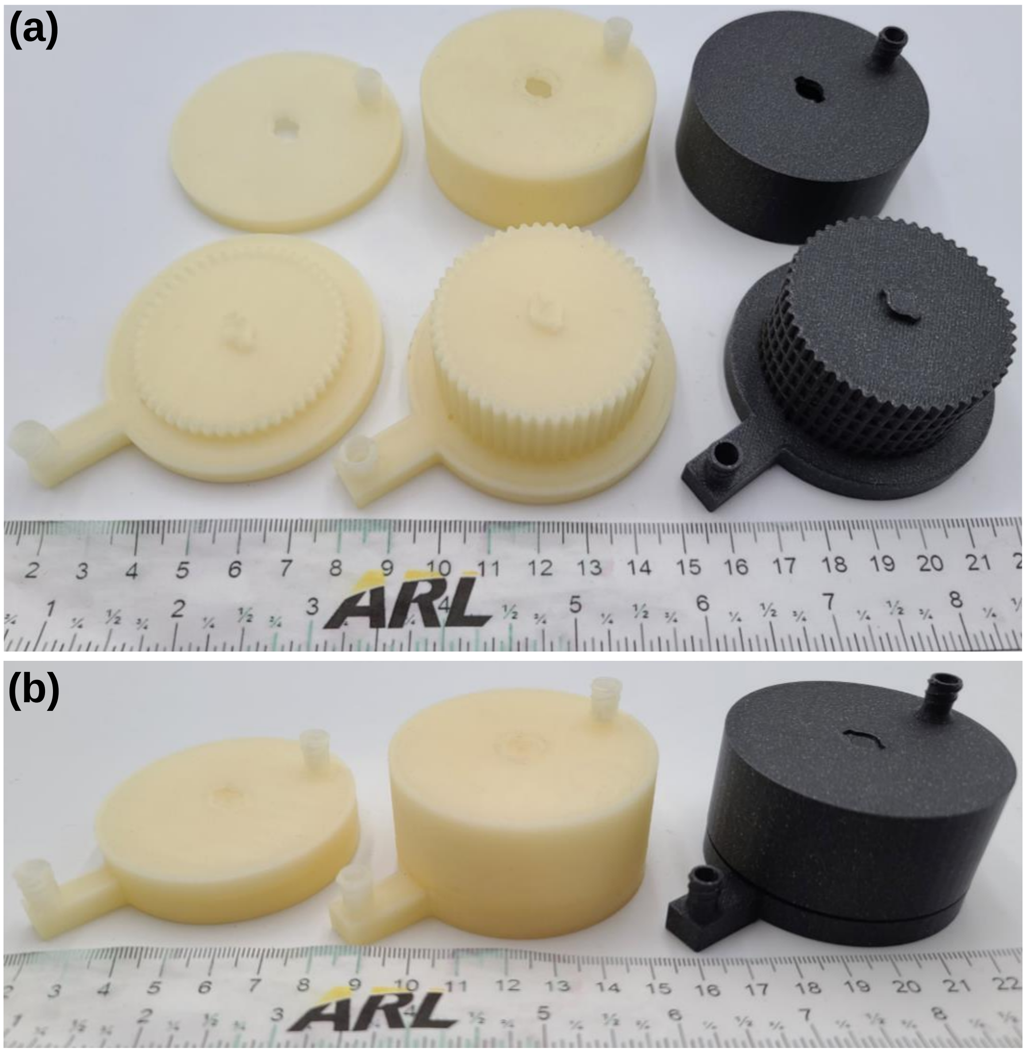


Figure 4. 3D printed mold parts and their assembly. (a) From left to right: single-belt BVOH mold, five-belt BVOH mold, and five-belt PLA mold with their respective part B in the top row and part A in the bottom row. (b) From left to right: assembled single-belt BVOH mold, five-belt BVOH mold, and five-belt PLA mold.

2.3 Resin Infusion and Cure

The reinforcement was first cut to a rectangular shape of either 445 × 4 mm for the single-belt mold or 445 × 24 mm for the five-belt mold. The reinforcement was then tightly wrapped around part A of the mold three times and the ends were held in place by brief exposure to a soldering iron that melted and fused the ends together (Figure 5a). Part B of the mold was then placed on top using the alignment feature to position the Luer locks on opposite sides, allowing for resin flow across the mold (Figure 3d). The two parts were held in place by the application of four C-clamps that reduce the leakage of resin through gaps at the interface between the two parts (Figure 5b). The urethane PMC 780 DRY resin was then mixed in a beaker in a 2:1 ratio according to the manufacturer instructions and degassed under vacuum. The 20 mL of mixed resin was then transferred to a syringe with a Luer lock fitting that was subsequently screwed onto the filling port on part A of the mold. A vacuum line was attached to the resin outlet Luer lock port on part B of the mold (Figure 6). As the mold was evacuated through the outlet vacuum line, resin began flowing through the mold due to atmospheric pressure on the syringe plunger. Resin was allowed to flow through the mold cavity until a bubble-free flow was observed in the outlet tubing, at which point the infusion ceased and the material cured at room temperature for 48 h.

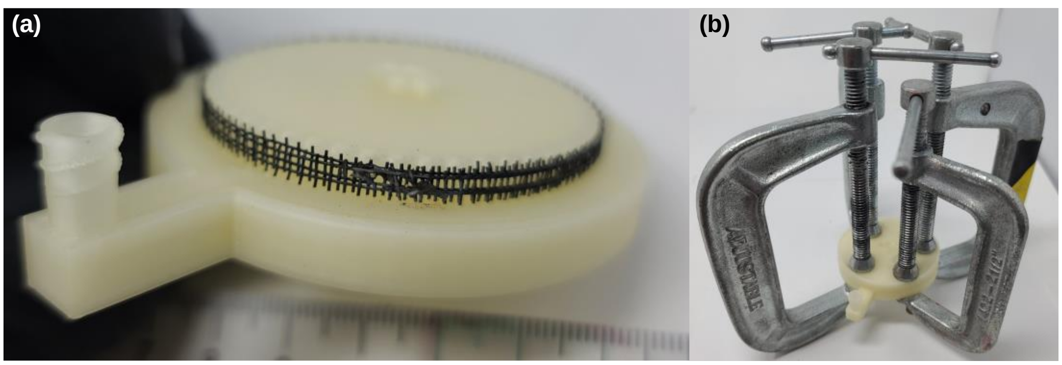


Figure 5. (a) Reinforcement wrapped around part A three times with the ends held in place by the melting of the reinforcement coating. (b) Part B placed on top of part A and secured with C-clamps.

For comparison, an additional set of belts were made using the BVOH mold without reinforcement. Belts were also made using only reinforcement material. For these belts, the reinforcement material was wrapped three times around part A of the five-belt mold, melt-bonded at its ends, and then cut into five 4-mm-wide individual belts.

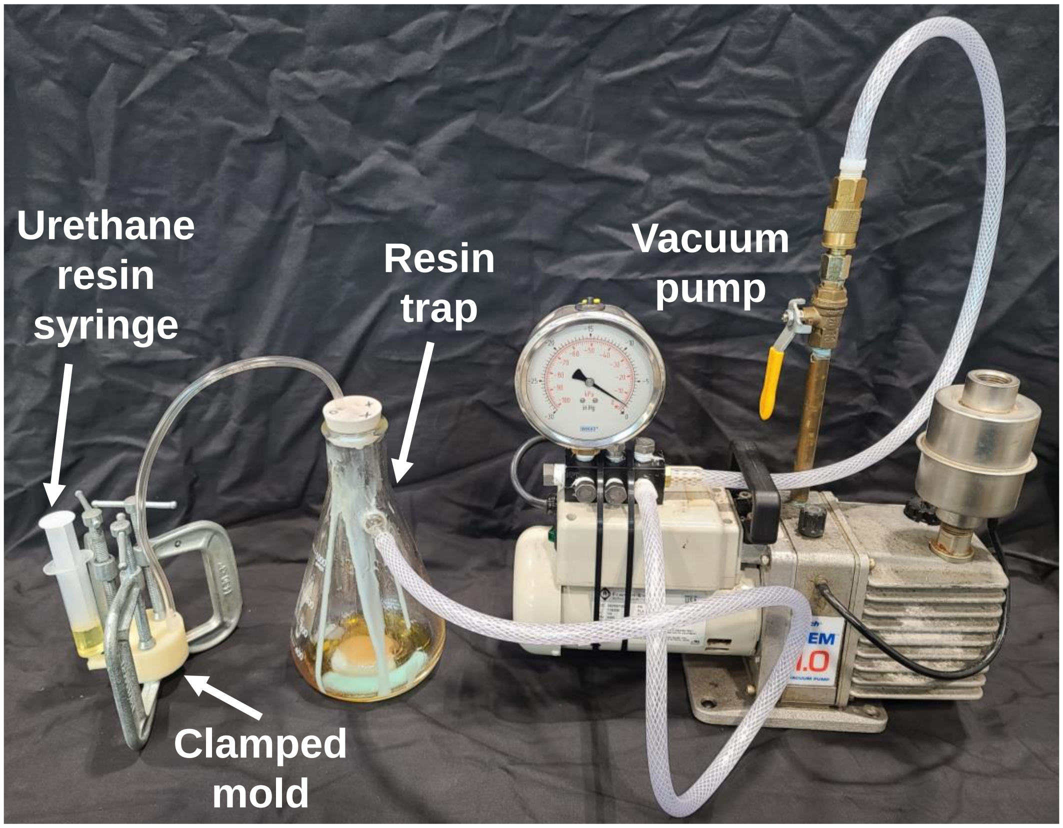


Figure 6. Resin infusion setup showing the syringe and vacuum connections.

2.4 Part Removal from Mold

For dissolvable BVOH molds, the cured assembly was placed in a 3.5-L stirring bucket of water. The mold was fully dissolved within 4 h, leaving behind the cast and cured belt. For the five-belt mold, a scalpel was used to initiate a cut between each belt along the circumferential separation line, followed by scissors to complete the cut around the full circumference of the belt.

For the nondissolvable PLA molds, mechanical destruction was used to separate the part from the mold (Figure 7). Experiments were performed with and without WD40 (San Diego, California), used as mold release and applied to the mold prior to casting.

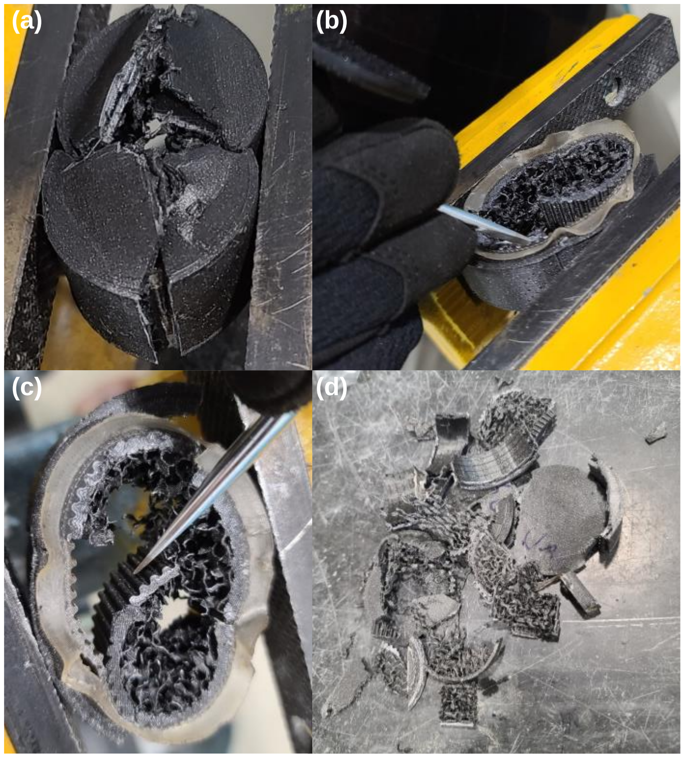


Figure 7. Mechanical removal of a five-belt part from a PLA mold. (a) PLA mold placed in a vise, (b) removal of the PLA mold, (c) peeling of the PLA mold away from the toothed belt, and (d) PLA mold pieces after removal.

2.5 Tensile Testing

Comparative static tests were performed by suspending belts under a constant load of 1.58 kg (15.5 N of force) and visually capturing their relative stretch. The belts tested under static conditions were an unreinforced cast belt, reinforced cast belt, and benchmark commercial belt. The commercial belt was made into a closed loop of the same diameter as the cast belts by clamping the belt ends with a pair of vise grips.

An MTS Synergie (Eden Prairie, Minnesota) load frame equipped with a 5-kN load cell was used to test the belts at 10 mm/min after preloading the belts with 1 N of force. Side-clamp style grips were used to hold steel chains that allowed for the loading of the belts as a link between the chains (Figure 8). The benchmark commercial toothed belt was tested directly in tension with a gauge length of 73 mm, approximately equal to half the circumference of the fabricated toothed belts.

Load frame results are reported as stress versus strain. Stress is calculated by normalizing the measured force by the minimum belt cross-sectional area, which is nominally 0.65 × 4 mm. Strain is calculated by dividing the load frame displacement by half of the belt circumference (since the belt is tested as a loop).

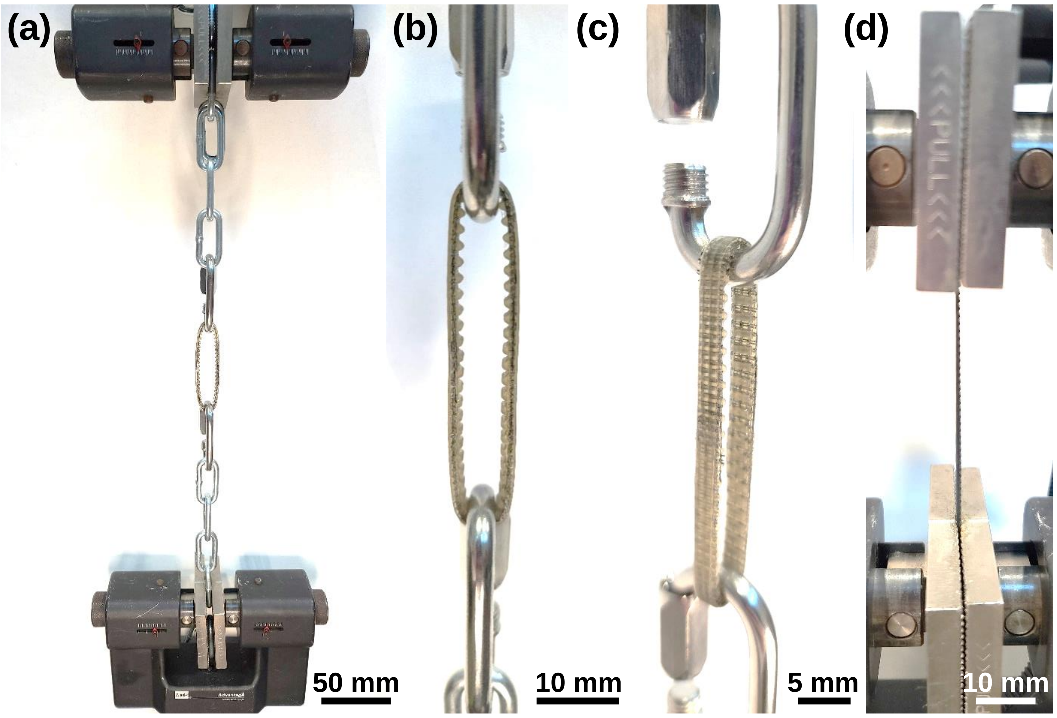


Figure 8. Photographs of load frame tensile testing. (a) Steel chains held between grips, (b) belt positioned between chain links, (c) side view of open links allowing the belt to be loaded, and (d) benchmark belt undergoing direct tensile loading.

3. Results

3.1 Extraction and Separation of Belts

Figure 9 shows belts extracted from the PLA mold. The adhesion between the urethane and the PLA prevented the simple separation of parts A and B of the mold. To remove the mold, it was compressed in a vise, cracking the brittle PLA and making it possible to peel the polymer away from the toothed belt (Figure 7c). Because the belt is so thin and flexible, it was able to survive this destructive extraction process. The specimen with mold release resulted in a low-quality part with evidence of poor wetting of the urethane to the reinforcement (Figure 9, right), suggesting that the mold release also coated the reinforcement. Therefore, mold release is not recommended for this application.

The fabricated belts from BVOH are shown in Figure 10. Each separated belt contains at least two continuous fibers in the hoop direction. The surface quality and geometric accuracy of the belts is excellent.

Figure 9. Five-belt stack extracted from PLA mold (left) and from PLA mold coated with WD-40 (right).

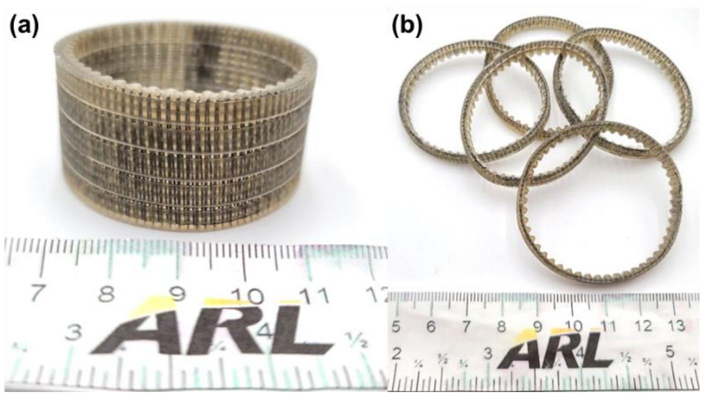


Figure 10. (a) Five-belt stack after removal from mold and flash removed. (b) Five individual belts obtained from the stack, ready for testing or use.

3.2 Mechanical Behavior

Static tensile results are shown in Figure 11. The belt without any reinforcement stretches significantly, to approximately 1.7 times its relaxed length, under the applied load while the two reinforced belts do not.

Figure 11. Static belt testing. (a) Belt fabricated without fiber reinforcement, (b) fabricated urethane belt with fiberglass reinforcement, and (c) benchmark belt with fiberglass reinforcement.

The load frame results are displayed in Figure 12 to compare the performance of the fabricated, reinforced toothed belts with others. The unreinforced cast belt (red line) exhibits a very low elastic modulus, requiring very little load to undergo significant extension. It also is very extensible, with a manufacturer-rated maximum elongation of 750%. The experiment stopped at 30% strain without bringing the sample to failure. The reinforcement by itself (blue line) is significantly stiffer than the unreinforced belt and does not undergo significant extension prior to failing. The reinforcement by itself has a jagged breaking profile due to the failure of individual loops of the reinforcement as well as the individual fiberglass fibers failing. The benchmark commercial belt (green line) underwent the most rapid loading and had the least extension before failure. The reinforced cast belt (black line) underwent a more gradual loading than the reinforcement by itself yet had a similar ultimate strength. The reinforced cast belt is significantly stiffer than the unreinforced belt. Table 1 compares strength and Young's modulus for the different belt configurations. Modulus is estimated as the slope of the stress–strain curve as the maximum stress is approached. The results show that the reinforced belt is less stiff and strong than the commercial belt, but also dramatically stiffer and stronger than the unreinforced belt. Specifically, the commercial belt is 5 times stiffer than the cast reinforced belt, while the cast reinforced belt is 65 times stiffer than the unreinforced belt.

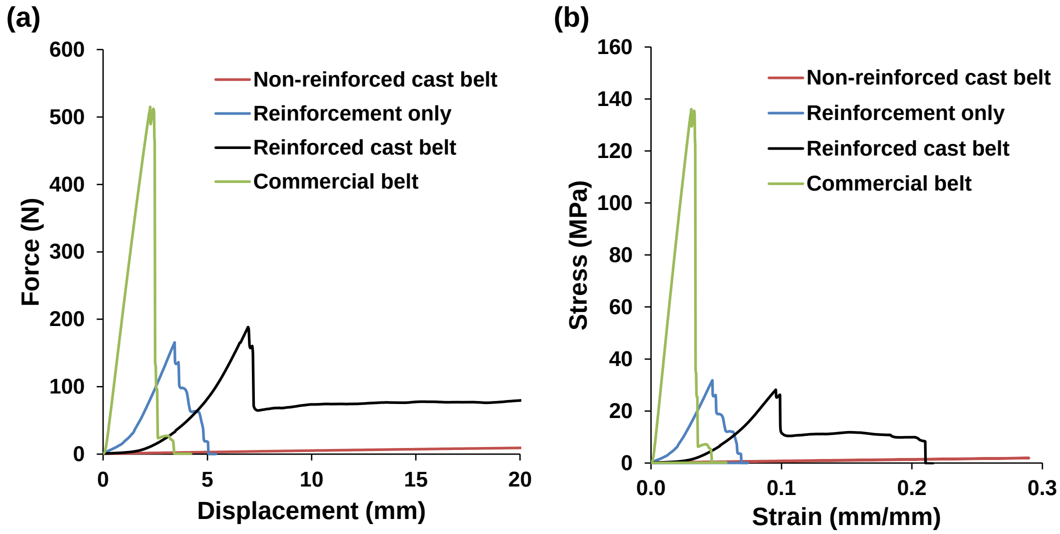
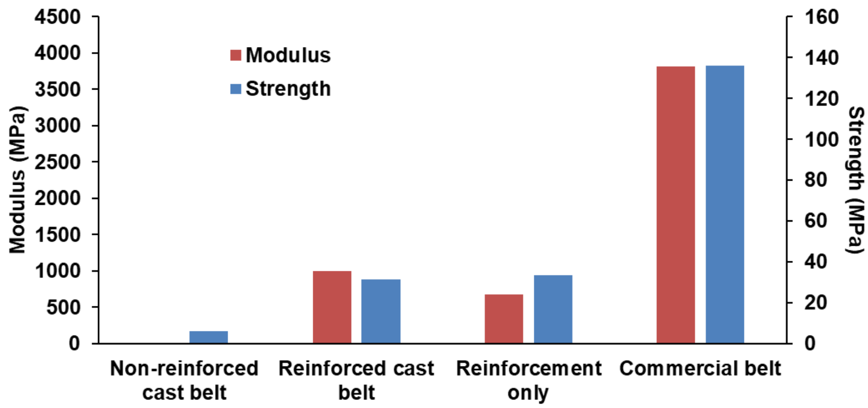


Figure 12. Representative tensile testing results comparing the contributions from the reinforcement and urethane. (a) Force–displacement and (b) stress–strain.

Table 1. Comparison of estimated Young's modulus and strength for different samples. The nonreinforced strength value is from manufacturer strength data for the PMC780 DRY resin system. Data for reinforcement and reinforced cast belt are average values from three experiments.

Sample	Modulus (MPa)	Strength (MPa)
Nonreinforced cast belt	10.5	6.2
Reinforcement only	1001	31.5
Reinforced cast belt	678	33.3
Commercial belt	3821	136.1



4. Discussion and Conclusions

The method disclosed herein is used to fabricate reinforced toothed belts of arbitrary sizes using the freeform fabrication abilities of additive manufacturing. The 3D printing approach to fabrication is straightforward to design belts of various diameters, thicknesses, width, and tooth geometry (separation, roundness, depth, pitch, etc.) and well-suited for point-of-need manufacturing. A custom-sized belt can be fabricated in only a few days (with most of the lead time being resin cure time), and less than $10 in materials. This is a significant advantage for austere or remote conditions where replacement parts might take weeks or months for delivery.

The dissolvable BVOH molding technique was most convenient, leading to easy release of a high-quality belt. However, the mechanical removal of the PLA mold also worked reasonably well, despite some surface damage to the belt. A significant advantage of PLA is that it is more readily available than dissolvable filaments such as BVOH. BVOH is hygroscopic, which necessitates the use of a dryer both before and during printing, and nearly 10 times the cost of commodity PLA. Further design work on the PLA mold could be undertaken to make it easier to remove; for example, by minimizing mold thickness and inserting separation joints or fracture lines into the mold.

The results show that an unreinforced elastomer belt has extremely low stiffness and can undergo significant extension. In the application of toothed belts, low stiffness and high elongation can lead to tooth skipping, lag, or lash between the driving and driven sprockets, and overall limits the torque that can be transmitted via the belt. Therefore, the unreinforced belt is unlikely to be useful in most applications. Similarly, if a belt was directly 3D printed using a thermoplastic elastomer without reinforcement, it likely would be too compliant. In contrast, the reinforced cast belt provided significantly higher stiffness and strength compared with the unreinforced belt. The reinforced belt would likely have sufficient strength and stiffness for short-term use, such as for battle damage and repair applications. While the fabricated toothed belts herein were not as stiff as a benchmark commercial belt, higher strength and stiffness could be achieved by casting belts with additional layers of reinforcement.

The general molding scheme can be used to create belts from a variety of materials. The fiberglass mesh used in the present prototypes was selected to demonstrate a suitable reinforcement that can be readily sourced in all parts of the world, including remote or relatively underdeveloped environments. While fiberglass was used in this demonstration, any reinforcing fiber can be used including woven steel wire mesh, nylon fabric, or Kevlar fabric. Fabrics with a very low cover factor (significant open area) are preferred to enable resin infusion through the reinforcement to provide mechanical interlocking. It is also possible to pair these reinforcements with other resins. Generally, a resin durometer of 70A–90A is recommended to maintain sufficient flexibility. Two-part resins or adhesives are preferred, as they are most likely to cure inside the mold cavity. The BVOH mold can be heated up to 180 °C to accelerate cure without significant deformation. Two-part urethane and silicone chemistries are likely to meet these criteria such as those commonly used to prepare rubber casting molds.

List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
BVOH	butenediol vinyl alcohol copolymer
DoD	Department of Defense
PLA	polylactic acid
TPU	thermoplastic polyurethane

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