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MECHANICALLY BONDING AND THERMALLY RELEASING PRINT SURFACE FOR BIG AREA ADDITIVE MANUFACTURING

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Abstract

Part retention and removal are challenges for Big Area Additive Manufacturing (BAAM) systems, increasing production costs and impacting part quality. A part should remain locked to the print surface during processing and then be released for removal when processing is completed. However, a method for releasing large, multi-meter parts from the print surface on BAAM systems is nonexistent. This work presents a print surface with a mechanically bonding interfacial structure that locks the part to the print surface during processing and then thermally releases the part for removal. Design and process parameters were evaluated, and a model was developed as a design guide for industry implementation. A demonstration casting pattern was produced in a hybrid manufacturing machining center by iterating between polymer pellet-fed material extrusion and surface machining. The viable applications of BAAM can be expanded by improving the process and reducing costs.

Introduction

Industry adoption of Fused Granulate Fabrication (FGF) for the production of large scale polymer parts on the scale of multiple meters has grown rapidly since the development of the Big Area Additive Manufacturing (BAAM) system at Oak Ridge National Lab [1]. This Material Extrusion (MEX) process, uses a screw extrusion system to deposit low-cost and commercially available polymer pellets at flow rates up to 100x faster and at 10x lower cost than comparable Fused Filament Fabrication (FFF) systems [2]. Due to the scale of these systems, the printing process typically occurs on an environment that lacks thermal control, which can lead to the buildup of residual stresses that result in the part warping [3]. To prevent parts from peeling off the surface of the print bed, an increased bond strength is typically used when compared to smaller scale FFF systems [4]. However, current print surface bonding approaches are not always able to achieve a sufficient bond to retain the part during production. Furthermore, the increased bond can make part removal a challenging and time-consuming step of the process [5]. This work aims to solve these challenges through a print bed that uses mechanical interlocking to hold the part to the print surface, then allowing for easy part removal through a thermal release (Figure 1).

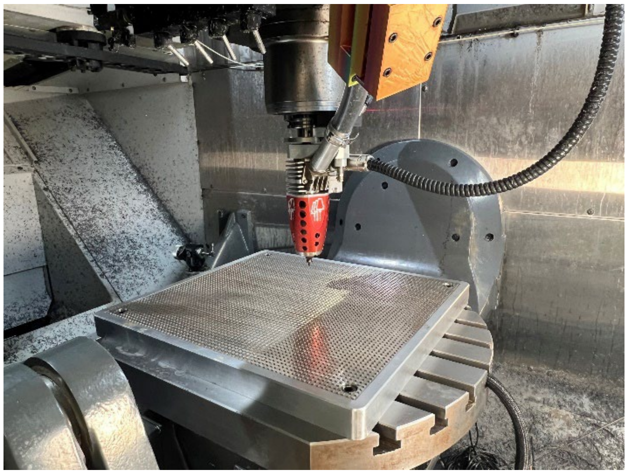


Figure 1. Mechanically interlocking print bed in a HAAS Machining Center.

Additive manufacturing processes typically fabricate parts using a layer by layer process so simplify process planning. However, when producing parts using layers, there is a tradeoff between productivity (thick layers) and surface finish (thin layers) [6]. The thick layers used in BAAM allow for the fast production of large-scale parts, but at the cost of increased error between the intended surface geometry and the geometry produced. To overcome this limitation, BAAM is often paired with machining to produce a hybrid additive and subtractive manufacturing process where machining can produce the needed surface finish and dimensional accuracy where required (Figure 2). Often, the machining will occur in a separate process after printing is complete which can limit reach and access and can require complex five-axis machining processes [7]. If the bond between the part and the print bed are strong enough to withstand machining forces, then it may be possible to alternate between additive material deposition and subtractive machining [8], [9]. Yet, increasing the bond requirements for the print surface compounds the challenge of part removal when processing is complete. Hybrid manufacturing processes are restricted by the lack of a print bed that achieves adequate bond during processing and allows the part to be released upon completion.

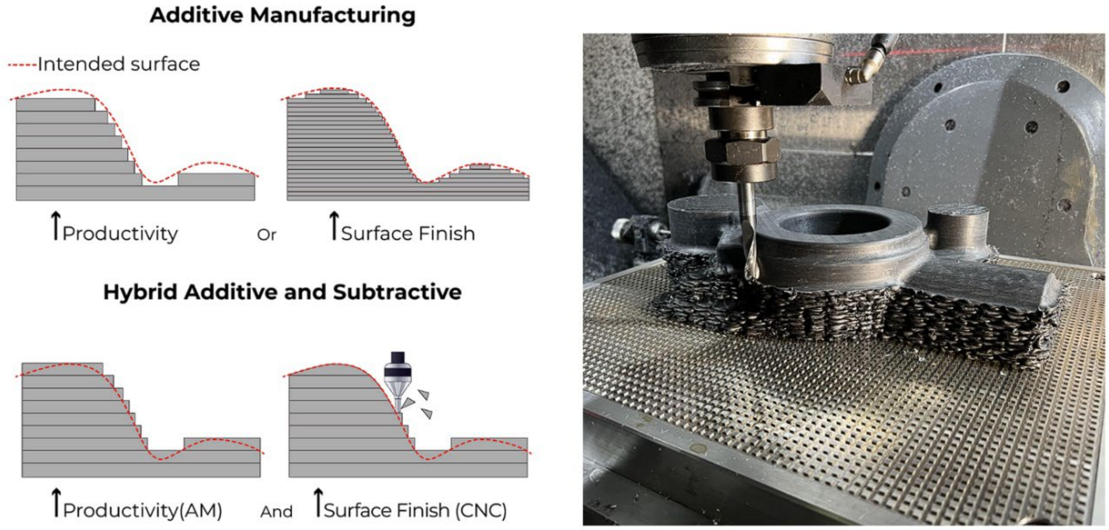


Figure 2. Hybrid additive and subtractive (machining) manufacturing processes allow for high productivity while meeting part surface finish and dimensional accuracy requirements.

There are currently three primary categories of print beds used on BAAM systems. The first is the use of a polymer sheet consisting of a material that will form a thermal fusion bond to the deposited material (Figure 3a). Polymer sheets can be retained using a vacuum system like the one used on the Cincinnati BAAM system developed in partnership with Oak Ridge National Lab, or can be adhered to a rigid surface as used by Loci Robotics [4]. A second approach invented by Thermwood Corporation consists of polymer pellets bonded to the print surface using an adhesive [10]. When the first layer is deposited, the part is locked to the print surface with both a thermal fusion bond and mechanical interlocking to a degree where a cohesive failure occurs in the print bed material before the bond fails (Figure 3b). Finally, mechanical interlocking has been used by CEAD B.V. and Caracol AM to create a pint surface bond [11]. This approach releases the part sing movement in the print bed to eliminate the mechanical interlocking, which may limit the ability to scale the size of this platform (Figure 3c).

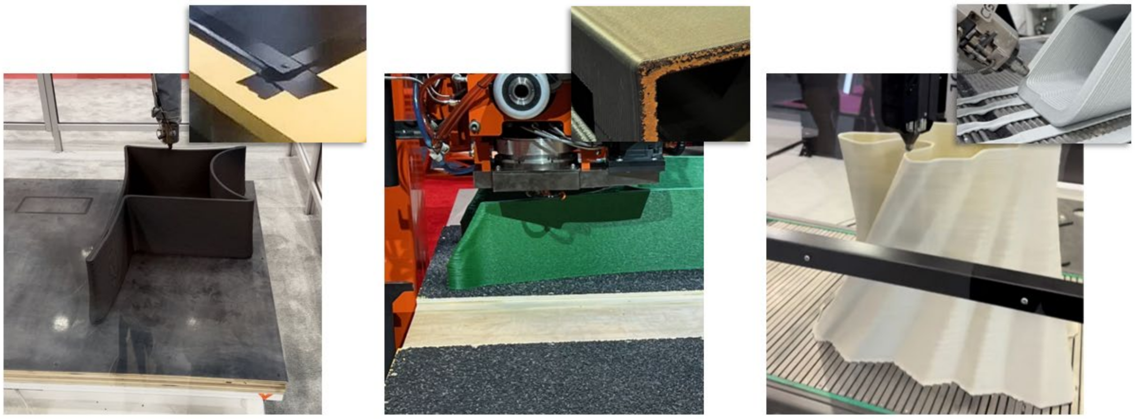

a) b) c)

Figure 3. Categories of print beds used in BAAM include a) polymer sheet, b) polymer pellets, and c) mechanical interlocking.

This work presents a method for achieving a mechanically interlocking bond that can be thermally released, without the need for moving parts. A print bed is produced with an array of dovetail pins that create overhanging geometry to lock the part in place upon solidification. This mechanical interlocking can be released by softening the polymer. A procedure for determining the appropriate release temperature for a thermoplastic material is presented. A casting pattern is produced by alternating between AM and machining to evaluate the ability for the print surface to retain and release the part under hybrid manufacturing processing conditions. Compatibility with multiple materials is evaluated by producing a high-density polyethylene (HDPE) part through hybrid manufacturing. This novel method for bonding and releasing a thermoplastic part during and after processing can reduce the cost due to scrap and post processing part removal. By improving the economics of BAAM, new applications can be made financially viable. There are also opportunities to use this approach for other applications, such as the production of multi-material components.

Solution Overview

Mechanical interlocking is used in various applications to form a structural bond in parts. Examples taken from woodworking (Figure 4), root structures found in nature, and in the retention of gas turbine blades demonstrate the versatility of this approach and act as inspiration for the print bed presented in this study. A pin feature is fabricated into the surface of the print bed with computer numerical control (CNC) machining with a specialty dovetail undercut tool. During the first layer of a print, molten thermoplastic can flow around the protruding pin, filling the overhanging region. As the thermoplastic cools, it solidifies and shrinks, compressing around the pin feature (Figure 5a). The part is retained by the small undercut region around the pin (Figure 5b). Heating applied to the bottom of the aluminum print bed will conduct through the print bed and warm the polymer (Figure 5c). When the polymer in the undercut region has softened due to heating, the mechanical interlocking is released, and the part can be removed (Figure 5d).

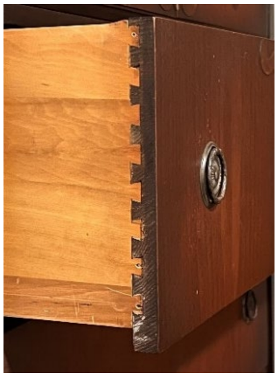


Figure 4. Mechanical interlocking using dovetails used in woodworking.

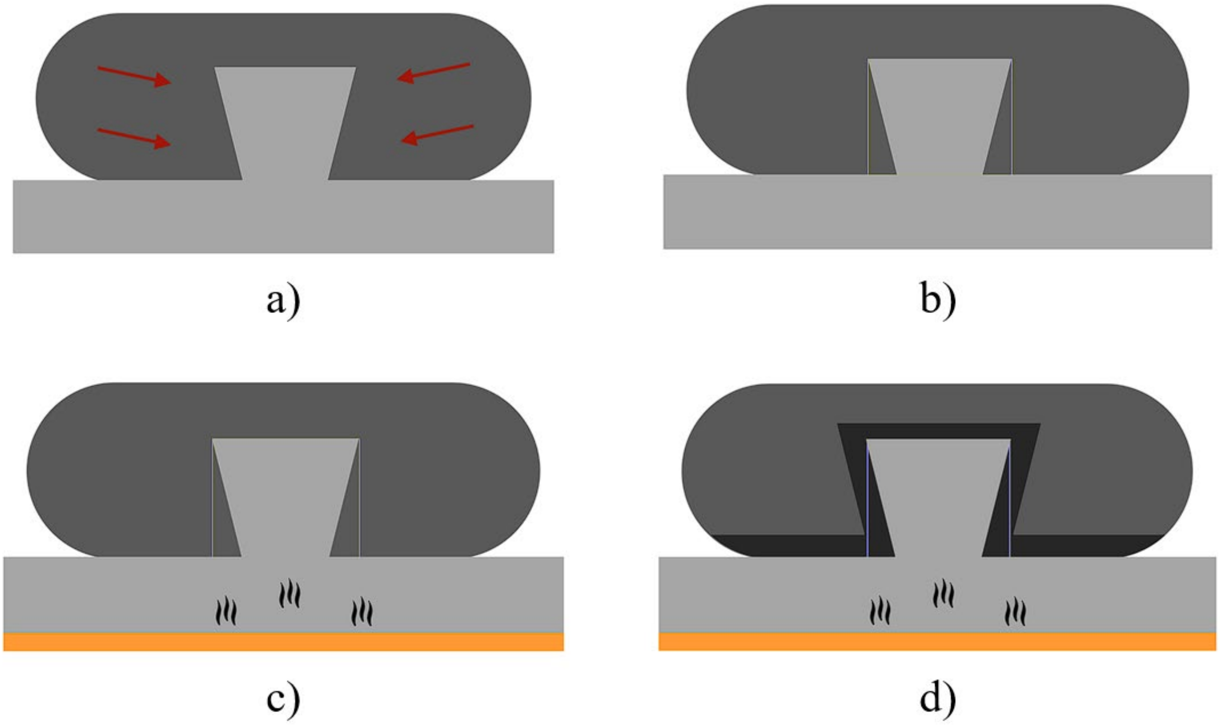


Figure 5. Mechanical bonding and releasing is achieved through a) thermoplastic solidifying around the protruding pins on the print bed, b) an undercut region around the pins retain the part during processing, c) rapid heating of the aluminum print bed heats the thermoplastic from the bottom, and d) the part is released when the thermoplastic in the undercut region softens.

Methodology

The temperature at which Acrylonitrile Butadiene Styrene (ABS) with a 20% carbon fiber content (ABS-CF) releases from a print bed was evaluated by applying a constant load of 17.8N using a spring scale. A sample section of the aluminum print bed with ABS-CF deposited having an interface cross section of 50.8 x 25.4 mm was placed under tension. A silicone heating mat supplied 30 W of heating to the bottom of the 12.7 mm thick aluminum print bed. A k-type thermocouple was inserted into a hole in the aluminum print bed to monitor the temperature at which the ABS-CF released from the print bed sample. Print beds with pin lengths of 0.5, 1.0, and 1.5 mm were tested with a pin included angle of 20°. Pins with a length of 1.0 mm were tested with included angles of 10°, 20°, and 30°.

A demonstration casting pattern was produced to evaluate the ability to produce a printed and machined sample, and part removal. The sample was produced following the procedure in Figure 6: 1) preheat the print bed to 100° C, 2) turn off print bed heating and deposit ABS-CF material, 3) machine surfaces, 4) heat print surface to release temperature, 5) wait for material in undercut regions to soften, and 6) manually remove the part. To evaluate the ability for other materials to be produced, an HDPE demonstration part was also produced. Samples were producing using the AMBIT XTrude (Hybrid Manufacturing Technologies) in a 5-axis HAAS machining center.

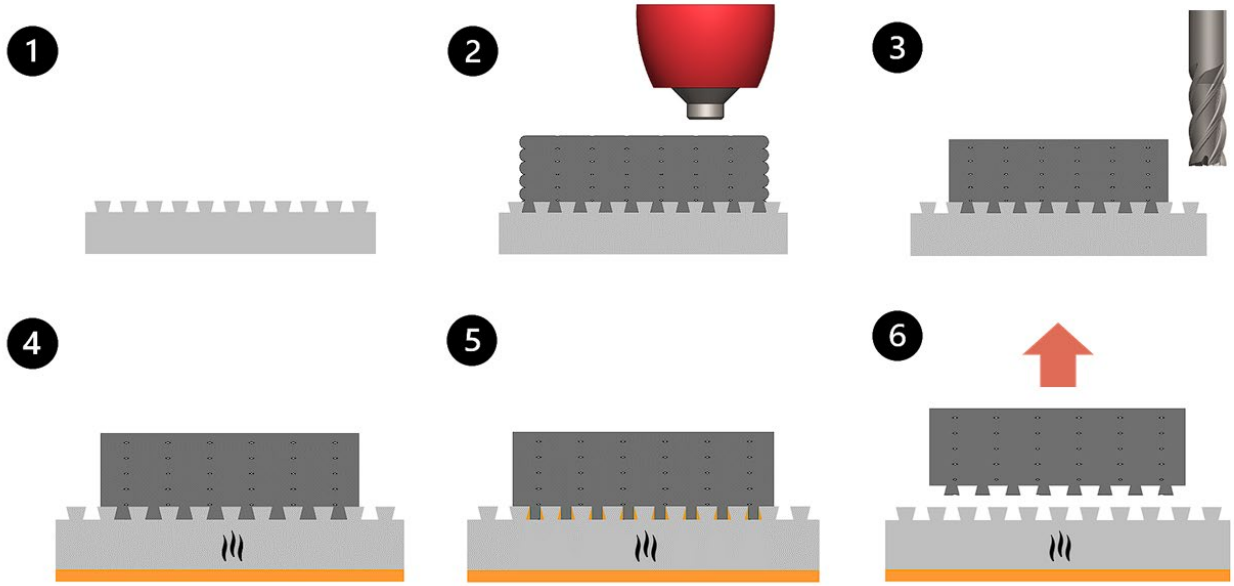
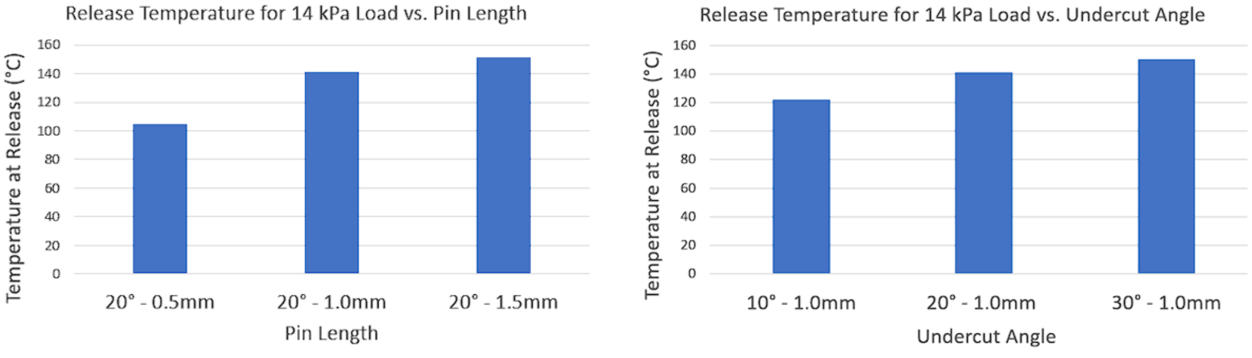


Figure 6. Process steps for producing and removing a part on the interlocking print bed.

Results and Discussion

Temperatures at which the ABS-CF released from the print surface are summarized in Figure 7. For dovetail pins with an included angle of 20°, increasing the pin length from 0.5 to 1.5 mm resulted in a 45% increase in the temperature needed to release the part with 17.8 N of force. Similarly, increasing the included angle from 10° to 30° on a 1.0 mm pin, the temperature needed to release the part increased 20%. In both cases, the increase in release temperature corresponds to an increase in the depth of the undercut. A constant, and rapid rate of heating is applied to the aluminum which has a relatively high thermal conductivity compared to the ABS-CF. The release temperature in all cases is less than the 230° C processing temperature of the polymer, suggesting that only a moderate degree of softening is needed to release the parts from the dovetail shaped pins.

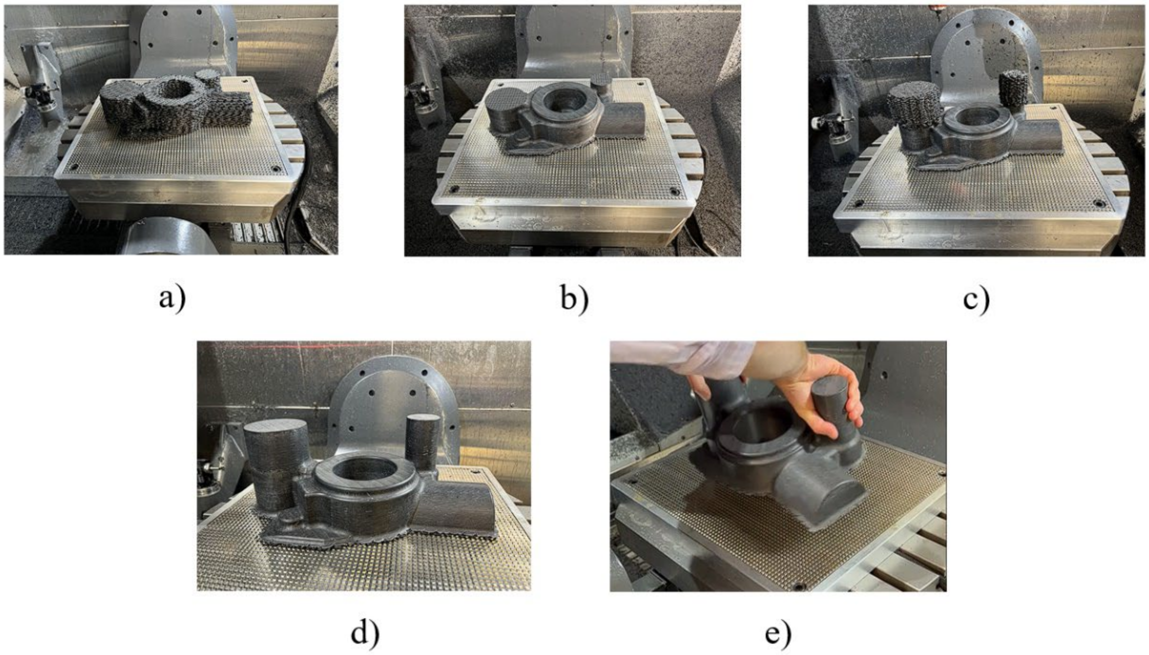


a)

b)

Figure 7. Release temperatures for an ABS-CF part on print surfaces with various retaining pin geometries at a constant load, a) varying pin lengths, and b) varying dovetail tool included angles.

A demonstration part was produced to test processing of a large scale component on the print bed. The aluminum print bed was produced with an array of 1.0 mm tall pins with an included angle of 20°, therefore a release temperature of 141° C was used. The print bed was pre-heated to 100° C, then turned off when printing started (Figure 8a). After the first section of the part was printed in ABS-CF, it was allowed to cool below its glass transition temperature, then machined using a 9.5 mm ball endmill with an amorphous diamond coating (Figure 8b). Dovetail pins with the same geometry as those on the pint bed were machined onto the horizontal interface where subsequent printing would occur. There is a potential for mechanical interlocking to be used to increase bond strength at cold interfaces, but further testing is needed to quantify the strength improvement [8]. Printing of the part was resumed (Figure 8c) and final machining of the top of the part was completed (Figure 8d). The print bed was heated, and the part was manually removed from the print bed when the release temperature was reached (Figure 8d). The print bed was able to retain the part consisting of heavy, solid sections as it cooled, and was able to withstand machining forces produced by aggressive chip loads of 0.25 mm. The ability to manually remove a part with a large first layer area without the need for additional tools demonstrates the potential for simplified post processing part removal.



a) b) c)

d) e)

Figure 8. A demonstration casting pattern was produced by a) Printing the lower section of the part, b) machining surfaces and interlocking interface, c) printing upper sections of the part, d) final part machining, e) part removal after thermal release.

Through the proposed process of alternating between printing and machining, challenges with reach and access of the machining tool are overcome [12]. By depositing the machining stock using additive manufacturing, an incremental part height can be selected based on the part geometry and available machine tool lengths in order to simplify machining operations. Additionally, the two tall features could be printed simultaneously and machined when complete, or they could have been printed one at a time. The additional process planning flexibility achieved through iterative hybrid manufacturing can be used to produce parts that would otherwise be challenging or impossible with out-of-envelope hybrid manufacturing. It is noted that, through iterative additive/subtractive manufacturing using the proposed method, a machining tool of relatively short length (e.g. 150mm/6in) could be used to create parts only limited by the print bed z-capacity and, more importantly, only require 3-axis CNC machining and still achieve reach and access top to bottom.

The capacity for BAAM systems to print a variety of commercially available engineering polymers is enabled by the versatile screw extrusion system. However, it is common to need material specific printing surfaces to achieve the required level of adhesion and release characteristics. HDPE is particularly challenging to print due to its lack of bonding to common print surfaces. A sample HDPE part was printed on the interlocking print bed presented here to demonstrate the broad range of materials that can be accommodated when mechanical bonding is used to retain the part (Figure 9). The HDPE sample was then machined, and finally removed from the print bed. A versatile print bed that can be used with an extensive list of materials can reduce the need for multiple print surfaces and save time when switching between materials.

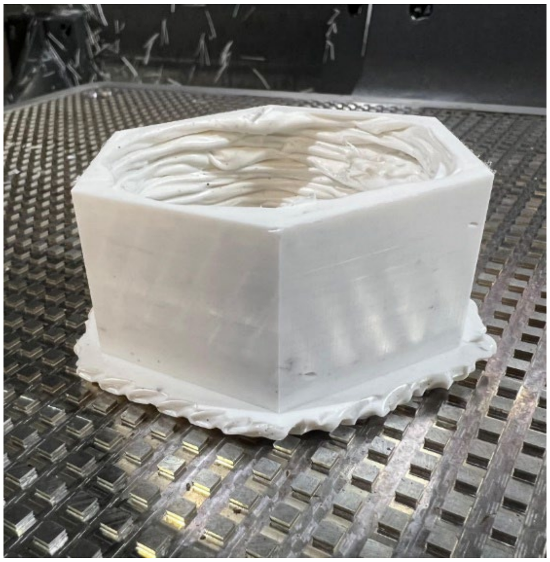


Figure 9. Demonstration sample printed in HDPE and machined.

The ability for mechanical interlocking to bond a range of materials together has applications beyond use as a print bed. Common manufacturing processes typically produce parts consisting of a single, homogeneous material with relatively similar properties throughout. Multi-material parts, on the other hand, consist of regions of unique materials to create a heterogeneous part. Designs that leverage these distinct material properties have the potential to meet performance requirements more effectively. Several samples were produced to demonstrate the ability to use the pin features from the print surface to produce multi-material parts consisting of dissimilar materials (Figure 10). Aluminum regions of the parts were machined with dovetail pins on the surface that would become the interface between material regions. Either neat ABS or an ABS+CF blend were deposited, then surfaces were machined. The resulting parts demonstrate the potential for the rapid production of metal-polymer parts in a hybrid manufacturing system.

Figure 10. Multi-material parts with aluminum and composite regions joined using mechanical interlocking.

Conclusions

A mechanically bonding print surface with the ability to release with heating was presented in this work. A method for determining the temperature at which a thermoplastic will release from the surface was evaluated using ABS-CF, and it was found that the part released above the glass transition temperature but below the melting temperature of the material. Both an increase in the pin length and the undercut angle showed a general trend of increasing the temperature needed to release the part with a constant force applied. A demonstration casting pattern was produced to assess the ability to produce and remove a large-scale part. HDPE was also used to produce a part, which is a material that is not compatible with many commercially available print beds.

Further evaluation is needed to quantify the strength of the bond of the print bed when the part is being processed. A model is needed to guide the optimal design of the interlocking features for specific applications. Those applications may extend beyond use as a print bed and include application in the production of multi-material parts consisting of dissimilar materials. Manufacturing process improvements are needed to expand the adoption of BAAM and hybrid manufacturing. By creating a robust bond during processing and releasing the part when complete, there is a potential for cost saving through reduced scrap and post-processing time.

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