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MECHANICAL INTERFACE FOR ITERATIVE HYBRID ADDITIVE AND SUBTRACTIVE MANUFACTURING

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Abstract

Additive and subtractive manufacturing systems for in-envelope production of large objects face challenges with respect to reach and access of cutting tools. One approach to overcoming this is iteratively alternate between additive and subtractive processes. However, polymer objects require cooling before machining, resulting in poor thermal welding when the subsequent polymer layer is deposited. This paper describes a method to enable iterative processing for in-envelope hybrid manufacturing that uses a mechanical bond to transition back to additive deposition after machining. This is accomplished using an AMBIT screw-extrusion head to additively manufacture a section of the object within a 5-axis machining center. After the object is machined, a dovetail cutting tool forms undercut geometry in the interface where plastic extrusion will resume. Upon polymer solidification, a mechanical interlock is formed. This work evaluates several undercut geometries for mechanical performance. This iterative approach to hybrid additive/subtractive manufacturing reduces machining complexity while maintaining structural integrity.

Introduction

Additive manufacturing (AM) of large composite objects has become possible through the productivity improvements achieved by the application of pellet-fed screw extruders and large diameter nozzles [1]. However, with layer thicknesses of multiple millimeters, the heightened stair step error reduces the ability to create surfaces accurately and increases surface roughness. Hybrid additive and subtractive manufacturing promises both high productivity and accurate surfaces with a fine finish through the deposition of thick layers followed by milling in a computer numerical controlled (CNC) machining center (Figure 1) [2]. A principal advantage of additive manufacturing is the ability to produce objects with complex geometry [3]. These complex shapes can lead to tool reach and access challenges for the subtractive machining operations that follow. A potential solution to the tool reach and access task is to iterate between additive and subtractive processes. However, this approach requires cooling the polymer object below the glass transition temperature before machining, which negatively affects the interlayer strength when resuming the additive process [4]. Improving the interlayer weld strength formed when depositing material on a cool surface has the

Figure 1. HAAS UMC750 machining center with a Hybrid Manufacturing Technologies AMBIT XTRUDE additive manufacturing system.

potential to enable the iterative additive and subtractive manufacturing of polymer objects.

Bonding is a complex process that typically consists of a mechanical, chemical, or thermal process, or a hybrid combination of several processes [5]. Currently, thermal fusion is the primary phenomenon forming the bond between layers in polymer extrusion AM. Since surface cooling reduces thermal energy in the system, weakening the bond strength, it is possible to improve the joint strength by re-heating the surface, but this approach risks deformation of the precision-machined section of the object [6]. A chemical method is also possible but would require the addition of a new process and the application of additional material. Since both the additive and subtractive processes can produce geometries needed for mechanical interlocking features, there may be potential to leverage their unique capabilities to form a mechanical bond. This research investigates the use of a mechanically interlocking feature at cool interfaces to act in conjunction with the current fusion welding between layers to improve strength.

Methodology

The proposed method uses undercut geometry formed using CNC milling tools to form a mechanically interlocking interface. There are six steps to the process presented here. First, a large-scale additive manufacturing system is used to deposit a section of the object (Figure 2a). The height of each section will be driven by the machining tool length and tool access to surfaces requiring machining. The first section of material is allowed to cool below the glass transition temperature, after which the surfaces can be machined to meet the design specifications (Figure 2b). An undercut geometry is then formed within the interface where further additive manufacturing will occur (Figure 2c). The undercut geometry is filled with molten polymer using the screw extruder (Figure 2d), and the subsequent section of the object is immediately deposited upon that surface (Figure 2e). It is critical that the new section of the object is deposited while the polymer in the undercut remains above its glass transition temperature to ensure a high-strength thermal fusion bond is formed. Upon cooling, a mechanical bond is formed by the undercut geometry and the new AM section can then be machined after cooling (Figure 2f). This process can be repeated as necessary until the entire object is formed.

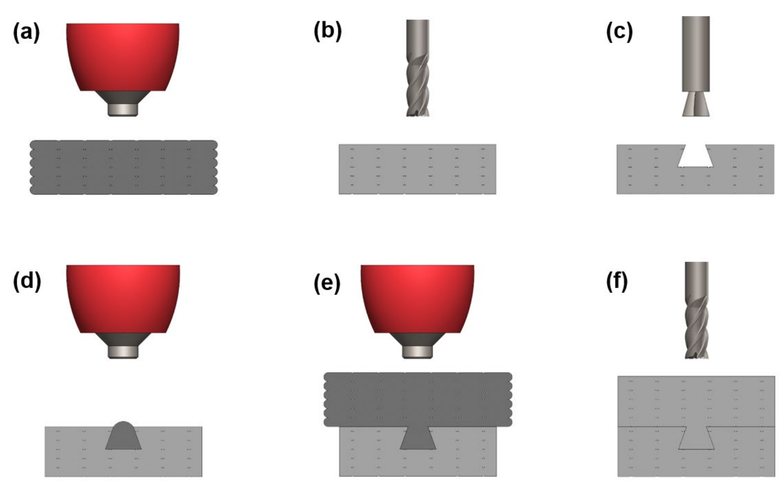


Figure 2. Proposed iterative process for hybrid additive and subtractive production of projects consists of a) AM deposition of a section of the object, b) cooling and machining, c) subtractive

machining of undercut geometry, d) AM filling of the undercut, e) AM deposition, f) final machining of the object surfaces.

As the ABS polymer containing 20% fill of chopped carbon fiber in the undercut geometry solidifies, it forms a mechanical bond between the two sections of the object. In this study, different geometries of the undercut feature are investigated. A 20° dovetail, 40° dovetail, and a T-slot profile are compared to a control surface with a flat face (Figure 3). The shallow angle of the 20° dovetail will form a less aggressive interlock than the 40° dovetail, and the T-slot is expected to provide the most aggressive interlock. However, a steeper undercut may be challenging to fill with molten polymer. This study will determine if the profile of the undercut slot results in a change in the tensile properties of the joint.

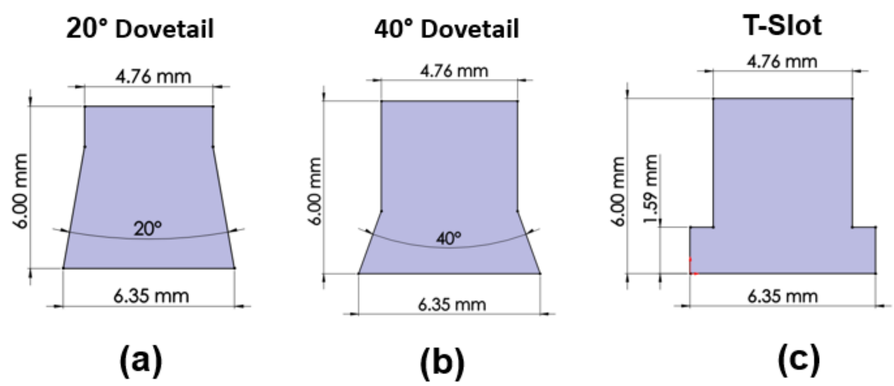


Figure 3. Profiles of undercut slots include a) 20° dovetail, b) 40° dovetail, and c) T-slot.

Tensile testing was conducted following ASTM D638 but with a modified Type III tensile bar geometry consisting of only the necked section of the bar (Figure 4) [7]. This adjustment was made to reduce material waste after preliminary testing verified that all tensile bars would break at the cool interface between the two sections of the object. Due to the reduced length, special care was taken to ensure the tensile bars were vertically aligned during tensile testing. A four-sided object was produced with three sides, each having a mechanical bond formed with one of the undercut profiles. The last edge acted as the control, containing no mechanical interface. Five tensile samples were cut from each side of the object (figure 4). Samples were conditioned for 24 hours in the lab environment at 25° C before testing in the universal testing machine (Test Resources 800LE2 Series, Shakopee, MN, USA) [8].

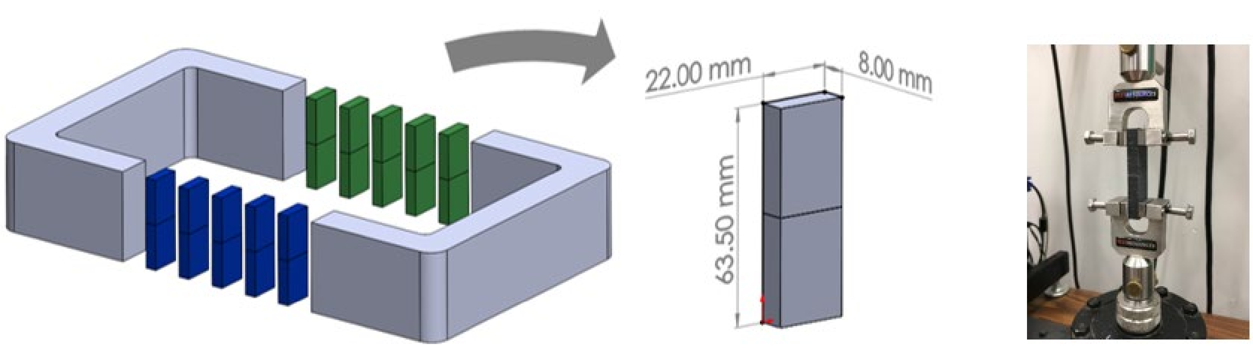


Figure 4. Tensile samples were cut from a four-sided object, with each side consisting of a unique sample set.

Results and Discussion

Figure 5 shows the production of the four-sided object for tensile bar production. This object was produced using the process as described earlier (Figure 2). In Figure 5c, the three sides containing the grooves are shown, each with unique undercut profiles. It should be noted that the interface surface was machined in the second step (Figure 5b). Interface machining was conducted to eliminate solidified material protruding in the z-direction that could lead to a collision with the AM nozzle when material extrusion resumed (Figure 5a). This machining step may affect the tensile strength of the cold interlayer weld.

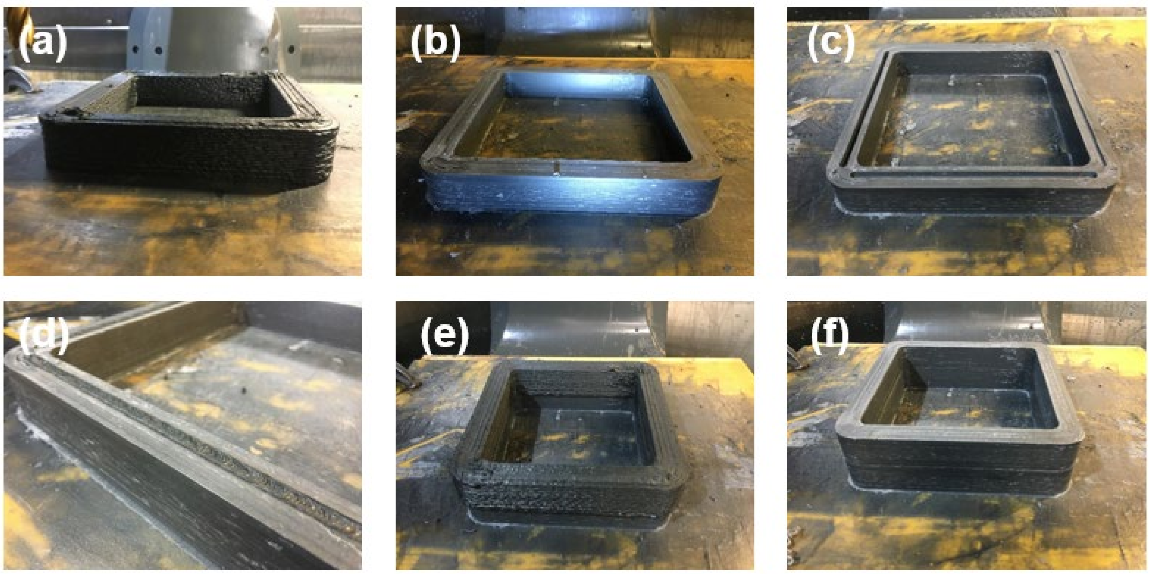
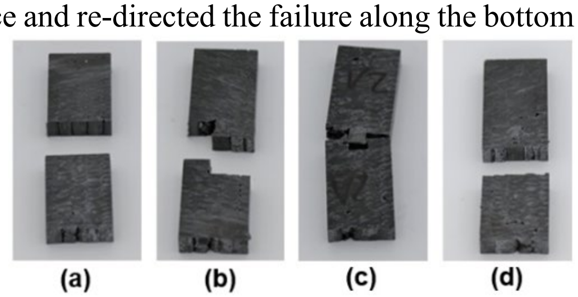


Figure 5. Demonstration of the proposed method of producing a mechanical interface to enable iterative AM and subtractive manufacturing consists of the process steps: a) AM deposition of a section of the object, b) subtractive machining of the surfaces, c) subtractive machining of grooves containing undercut geometry, d) AM filling of the grooves, e) deposition of another section of the object, f) final subtractive machining of the object.

Typical failures of the tensile bars from each sample set are seen in Figure 6. In every instance, the failure occurs along a portion of the interface between the two regions of the object. For the control sample set (Figure 6a), all failures occur along the cool weld layer. The T-slot interfered with the clean break along the cool interface and re-directed the failure along the bottom of the interlocking feature (Figure 6b). The 20° dovetail pulled out of the slot, while the 40° dovetail led to failure along the bottom of the groove (Figure 6 c & d). Failures through regions of the substrate where the material is not allowed extensive cooling are expected to result in higher ultimate tensile strengths (UTS) since reduced cooling time has



been shown to improve weld strength between layers [9]. Visual inspection of the T-slot samples showed incomplete groove filling, which may have reduced the mechanical interlocking that occurred on samples with that feature.

Tensile testing showed a significant increase in the mean UTS of 37% for the 20° dovetail and 41% for the 40° dovetail with ($P = 0.001$) and ($P < 0.001$) respectively (Figure 7). The T-slot did not result in a significant change to the UTS. The designer of a part often needs to assume a material strength for the object and would likely select the minimum strength along a cold weld. By increasing the strength along the cold weld interface, the assumed strength for the object can be increased. This would allow the designer to reduce weight or meet other functional requirements that would otherwise not be obtainable. While this method results in a significant and substantial increase in UTS, the strength remains less than half of the interlayer strength achieved when the material is not allowed to cool. This suggests that there is further work needed optimizing this method to improve strength.

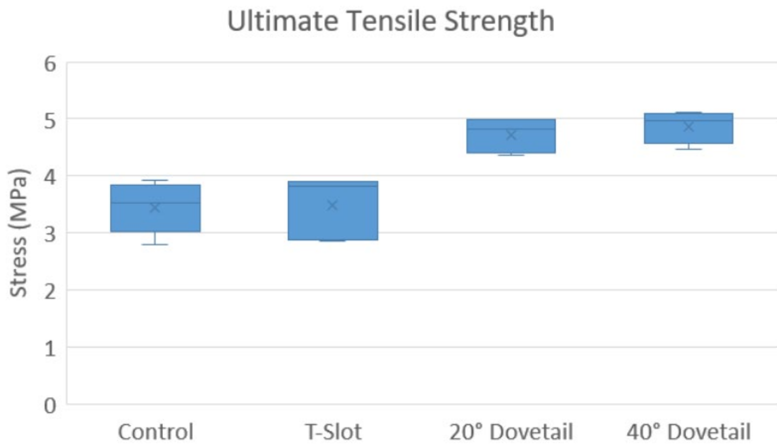


Figure 7. Ultimate tensile strength for each of the profiles.

A truss structure was also produced as a demonstration object using the proposed method (Figure 8). This object was manufactured using the same process steps outlined previously in this paper (Figure 2). A 20° dovetail was used as the mechanically interlocking root structure. While this object has a short enough height that machining could have occurred without stopping mid-process, it stands as a proof of concept for objects with a greater height. The truss shows that the process steps can be applied to objects with more complex geometry.

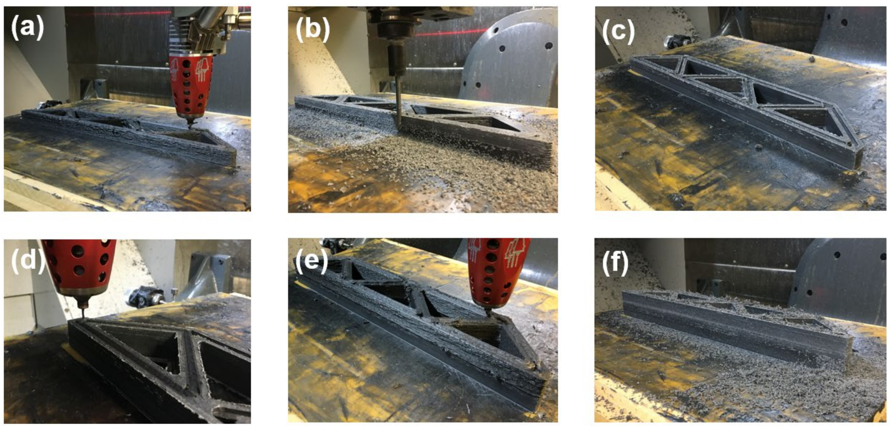


Figure 8. Demonstration truss structure produced by: a) AM deposition, b) machining, c) machining of 20° dovetail, d) AM dovetail filling, e) AM deposition, f) machining.

Visual inspection of the demonstration truss structure shows surfaces with finer surface finishes than those typically found on BAAM parts (Figure 9a&b). This object shows signs of porosity in thick sections due to the use of a large minimum toolpath length setting in the slicer (Figure 9c). Longer minimum toolpath lengths reduce the frequency of stopping and re-starting extrusion for each layer, reducing the overall production time and eliminating errors associated with short AM toolpaths.

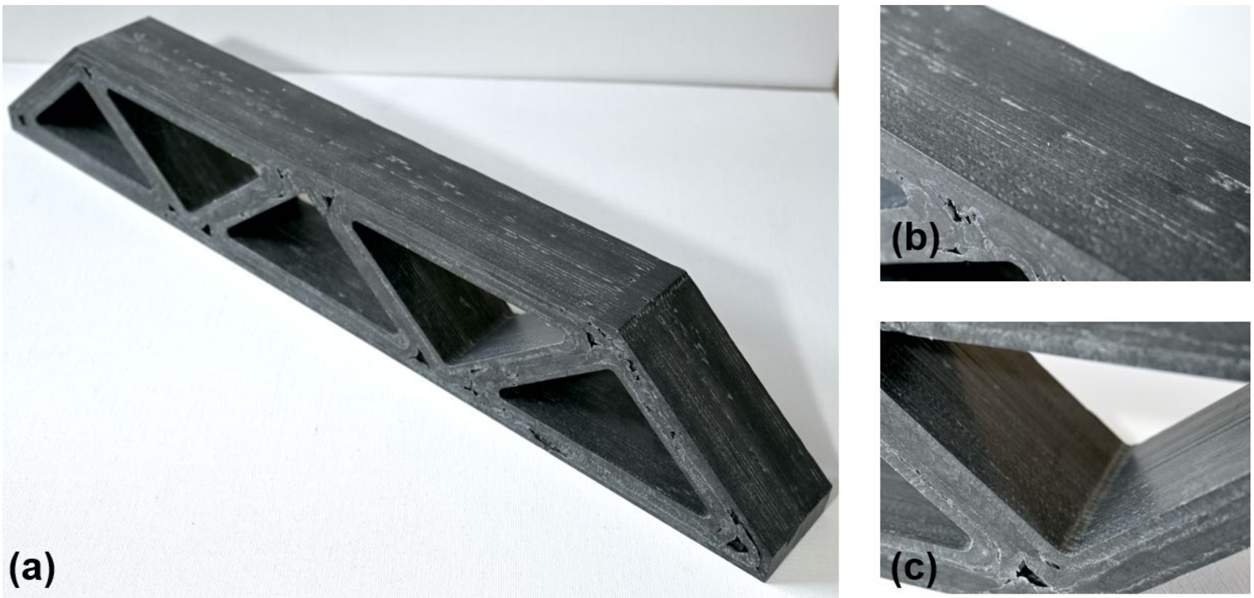


Figure 9. Images of the finished demonstration truss structure produced using iterative AM and subtractive manufacturing.

Conclusions

A method for improving the inter-layer strength of polymer AM objects using mechanically interlocking features is presented. These features were shown to significantly and substantially improve the ultimate tensile strength across a cool weld interface. Both the 20° and 40° dovetail profiles of the feature increased the UTS while a T-slot profile showed no improvement. The T-slot also showed signs of incomplete filling, suggesting that the small undercut features hampered the flow of molten polymer. A demonstration truss structure is also presented to show how iterative AM and subtractive manufacturing can be applied to produce large and complex objects with accurate surfaces and fine surface finishes.

The ability to iterate between additive and subtractive manufacturing has the potential to reduce the required tool lengths for large objects while simplifying process planning associated with subtractive tool reach and access, potentially avoiding the use of long tools, long tool holders or even avoid complex multi-axis machining. Moreover, the iterative method could enable limitless build heights; when those build heights are restricted by machinability reach and access. It could also allow for an intentional pause in printing to add embedded components, or enable a re-start when an unexpected downtime of the machine occurs due to breakdown or power failure. While the mechanical interface presented here improved the interlayer strength where the AM process was paused, the strength is still far below that of the ABS/CF material when deposited without a cooling pause. Further work is needed to improve the strength of this interface to match the other regions of the object more closely. This may be accomplished by further optimizing the profiles used to form the undercut geometry or applying other bonding processes such as chemical or thermal fusion.

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