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THERMALLY SWITCHABLE BUILD TABLE BY MECHANICAL INTERLOCKING FOR ADDITIVE MANUFACTURING

E. D. Weflen, F. E. Peters, M. C. Frank

Industrial and Manufacturing Systems Engineering, Iowa State University, Ames, IA 50011

Abstract

This work presents a method for achieving a thermally switchable bond on a build table for Additive Manufacturing using mechanically interlocking features. Removal of parts from the build table remains a challenge. Furthermore, the residual stress that develops as multiple layers are deposited in an ambient environment can lead to the part detaching from the build table if bonding is insufficient. To achieve ample part to build table bonding, undercut features are machined into a metal build table onto which the molten polymer is extruded. Upon solidification, a mechanical bond is formed. The part can then be easily removed through rapid heating of the undercut features, resulting in a loss of mechanical bonding. We present results from our lab-scale setup allowing fundamental studies of the core physics. The method can easily be scaled larger or smaller by proportionally sizing the undercut features to the plastic extrusion bead size and parameters.

Introduction

The production of large-scale polymer parts using the Additive Manufacturing (AM) process of Fused Filament Fabrication (FFF) has been implemented in industry to produce industrial tooling and end-use parts. Developed at Oak Ridge National Laboratory, the Big Area Additive Manufacturing (BAAM) technology allows for parts larger than the traditional capabilities of FFF systems by implementing a screw extrusion system and modifications that enable processing to occur without a heated chamber [1]. However, these large parts can be challenging to remove from the build table. Not only does the weight and size pose a challenge, but the high bond strength between the part and the build plate can make it challenging to release the part. The high bond strength can be attributed to the need to hold the part during printing and forces from subtractive machining [2], [3]. Small-scale FFF systems overcome these challenges by using a sacrificial raft, using print beds that can be peeled from the part, relying on differences in coefficients of thermal expansion to shear the interface, and using surface coatings that have thermally switchable adhesion, among other solutions [4]. Removing parts from the print bed remains challenging despite attempts to apply these approaches to large-scale AM systems. Current leading solutions include printing on a vacuum-retained sheet of polymer or material pellets adhered to medium-

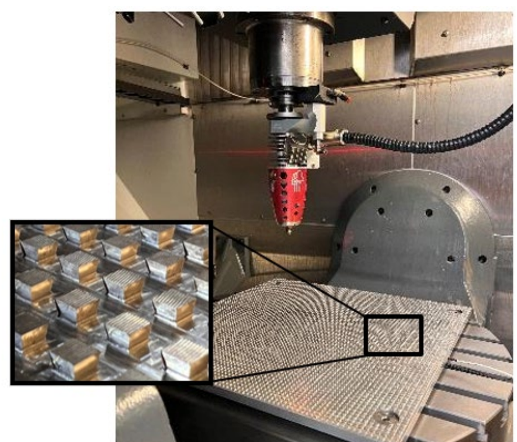

Figure 1. Hybrid Manufacturing Technologies AMBIT XTRUDE in a HAAS UMC 750 5-axis mill.

density fiberboard (MDF). Therefore, to improve the processing of large-scale parts, a print bed is needed to hold the part securely while processing but then easily release the part when processing is complete. A suitable solution does not exist that enables extreme bonding strength during processing and ease of removal when completed.

Figure 2. Mechanical Interlocking [8].

Switchable adhesion is an approach applied to situations where a single bond strength does not meet requirements [5]. In addition, mechanically interlocking features have been demonstrated as an approach to joining dissimilar materials produced using additive manufacturing (Figure 2) [6]–[8]. This study presents a method using mechanically interlocking features to produce a print bed with a thermally switchable bond. The print bed can be rapidly heated when processing completes, releasing the part. The resulting build plate possesses a greater bond strength during processing and easier part removal when processing completes than current solutions for large-scale AM. These findings result in a process improvement that can help enable the production of large-scale parts by improving process capability and reducing the processing time needed for part removal.

Solution Overview

The proposed method forms a mechanical bond using milled undercut geometry in a metal build plate produced using Computer Numerical Control (CNC) machining (Figure 1). The molten polymer is deposited on the build plate, filling the undercut region (Figures 3a & b). Upon solidification, a mechanical interlock is formed. This bond must be able to withstand the forces developed during both additive processing and optional machining. When the processing on the part is complete, it can be removed by rapid heating of the print bed, which softens the polymer along the metal-polymer interface. When the polymer within the undercut region softens sufficiently, the mechanical interlocking forces drop, allowing easy part removal.

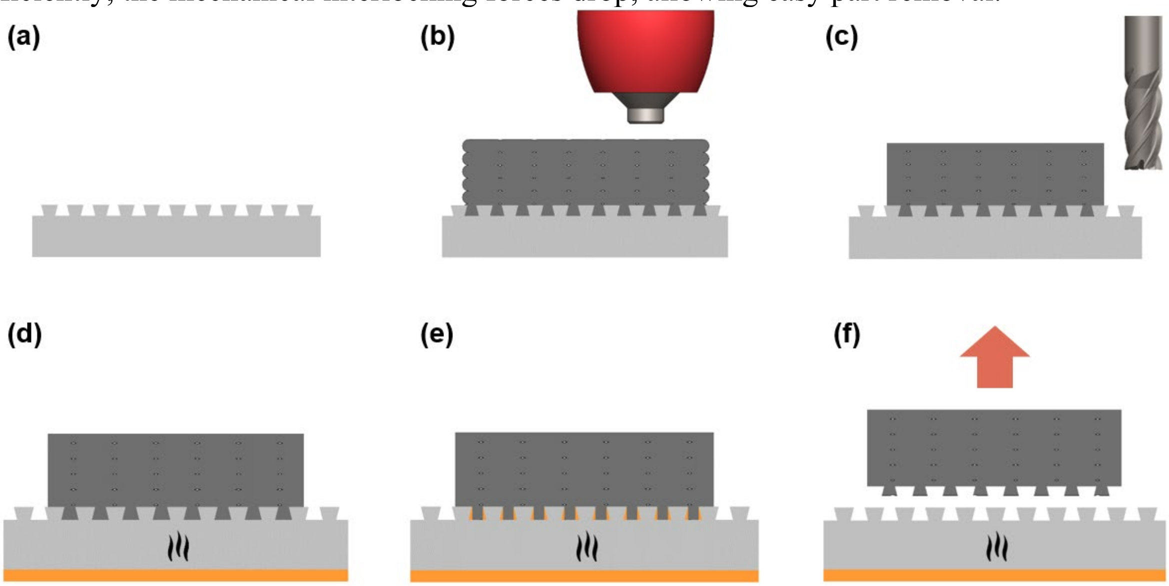

Figure 3. The process steps for the proposed print bed are: a) preheating the print bed, b) depositing the polymer material, c) machining of surfaces, d) rapid heating of print bed, e) polymer softening in the undercut region, and f) removal of the completed object.

The process consists of six key steps when implemented in a hybrid additive and subtractive environment (Figure 3). The empty print bed with undercut features is preheated to 100° C to ensure the polymer can flow into the undercut regions (Figure 3a). The extrusion system is used to deposit the part on the print bed (Figure 3b). The part is allowed to cool to a temperature needed for machining, which can occur with the object still on the print bed (Figure 3c). When the part is ready to be released from the print bed, the heating elements can be turned on to rapidly heat the aluminum print bed (Figure 3d). When the print bed heat reaches a critical level, the polymer in the undercut region will soften, resulting in the bond strength switching to a lower level (Figure 3e). The completed part can be removed from the print bed with a force that is not only much less than would have been required prior to softening the polymer in the undercut region but much less than current solutions for large-scale AM (Figure 3f). A detailed view of the mechanically interlocking between the polymer part and the metal print bed can be found in Figure 4. The presented method allows for high bond strength while the part is being processed on the print bed and the bond strength to be reduced to release the part when processing is complete.

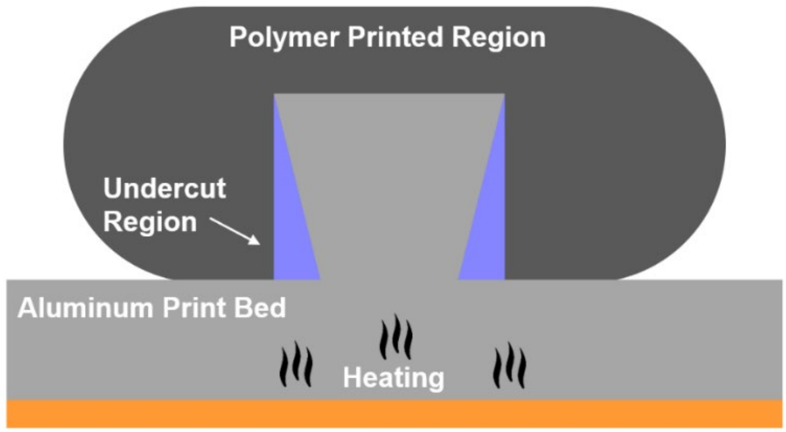

Figure 4. Detail of the mechanical interlocking between the metal print bed and the polymer region.

Methodology

A prototype print bed was produced from a 12.7 mm thick plate of 6061 aluminum with a length and width of 457 mm (Figure 1). Intersecting grooves (0 ° and 90 °) were machined with a width, depth, and spacing of 3.2 mm using a carbide flat end mill. A dovetail undercut end mill was used to mill a 10° from vertical undercut. Seven strip heaters were mounted to the back of the build table with a total heat output of 2,100 watts. The heaters and a k-type thermocouple were wired to a temperature and process controller that used a proportional-integral-derivative (PID) control loop to reach the set temperature.

The ability to withstand printing, bowing, and cutting forces experienced during processing was evaluated by printing a 400 x 24 x 50 mm strip (Figure 5a). One-half of a bead width was machined off on all exposed faces. Two of these test parts were produced, one neat ABS and one from ABS containing a 20% chopped carbon fiber fill (HM Technologies, McKinney, TX, USA). The print bed was preheated to 100° C before printing, then switched off.

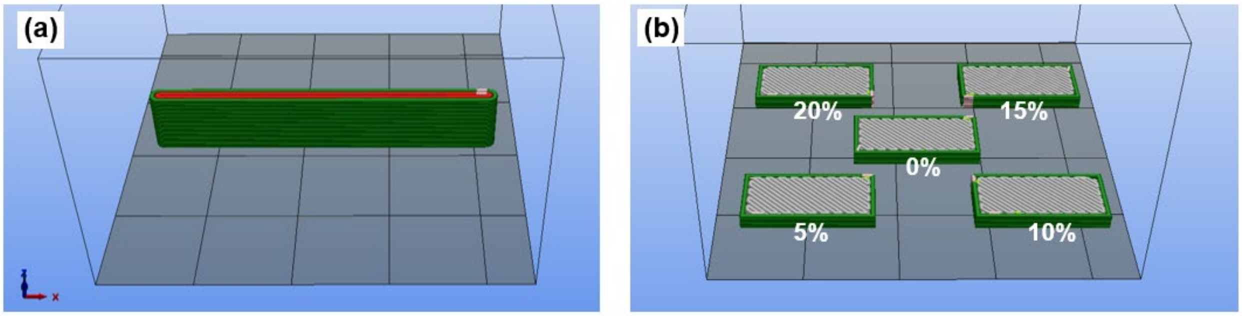

Figure 5. Simulated process plans from the ORNL slicer of the a) test strip and b) test patches.

Part removal was evaluated using the two printed parts 400 mm long.

To evaluate how carbon fiber content affected removal, five patches (76 x 452 x 13 mm) were printed using different carbon fiber contents (0%, 5%, 10%, 15%, 20%) by blending the neat ABS and ABS/20% CF pellets (Figure 5b). The PID process controller was set to 250° C and parts were removed by hand when the print bed reached temperature. The print bed was visually inspected after removal.

Tensile testing was conducted to quantify the bond strength of the mechanical interlocking features. A custom tensile test geometry was used to simulate this print bed application (Figure 6). Undercut features with identical geometry to those on the print bed were cut into an aluminum extruded bar (Figure 6a). Then, ABS/20%CF material was deposited using the AMBIT XTRUDE system with the same settings for printing the test samples (Figure 6b). Three samples were cut from the center section of the test bar and went through tensile testing in a UH-F300kNX universal testing machine (Shimadzu Corp., Japan) with a strain rate of 5 mm/min (Figure 6c).

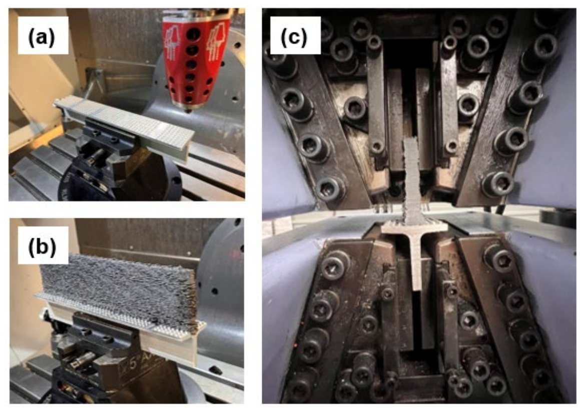

Figure 6. Tensile test sample preparation included a) undercut features cut into extruded bar, b) polymer deposited on print surface, c) tensile testing in a universal testing machine.

Results and Discussion

The long test strips printed in neat ABS and an ABS/CF composite both performed well during the processing evaluation (Figure 7). Parts remained firmly attached throughout both the additive extrusion process and the machining. The samples were removed by heating the print bed to 250° C, at which point the operator could pull the samples off by hand. Both samples were successfully removed by hand without the aid of any tools. When evaluated on a calibrated granite surface plate, the samples did not exhibit any significant signs of distortion (e.g. curling/bowing). The neat ABS sample showed signs of deformation immediately around the areas where the undercut pins were removed; potentially a sign that the neat ABS may not have required as high of a temperature. Overall, this experiment successfully demonstrates the ability of the print bed to both 1) withstand the forces produced during both the additive and subtractive manufacturing operations and then 2) allow removal with exceedingly small manual effort.

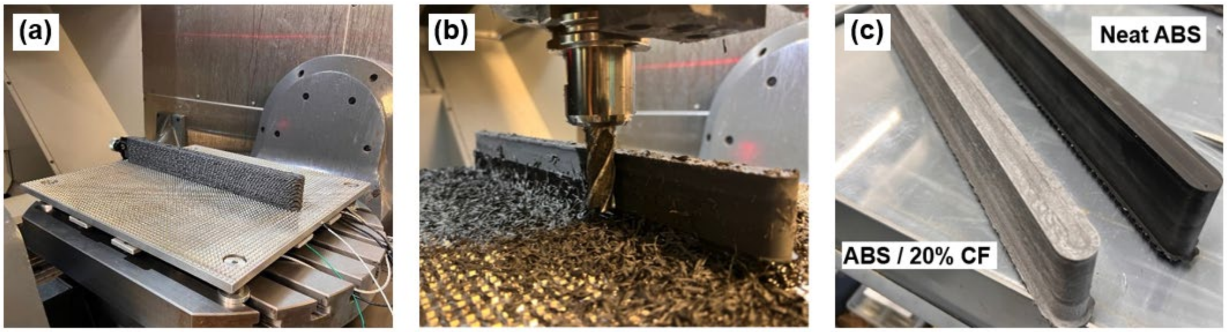

Figure 7. Print bed testing of the a) AM process, b) machining, and c) part removal.

Evaluation of parts produced with five different levels of chopped carbon fiber showed that all samples could withstand processing forces and remained bonded to the print bed (Figure 8a). Upon removal of the parts, the sample produced using neat ABS left a residue on the print bed and was deformed in the region surrounding the pin extraction locations (Figure 8b). All samples containing chopped carbon fiber were removed by hand without leaving a residue or apparent deformation. The neat ABS sample may need to be removed from the print bed at a temperature lower than 250° C. Further evaluation of the part removal temperature for different materials is needed.

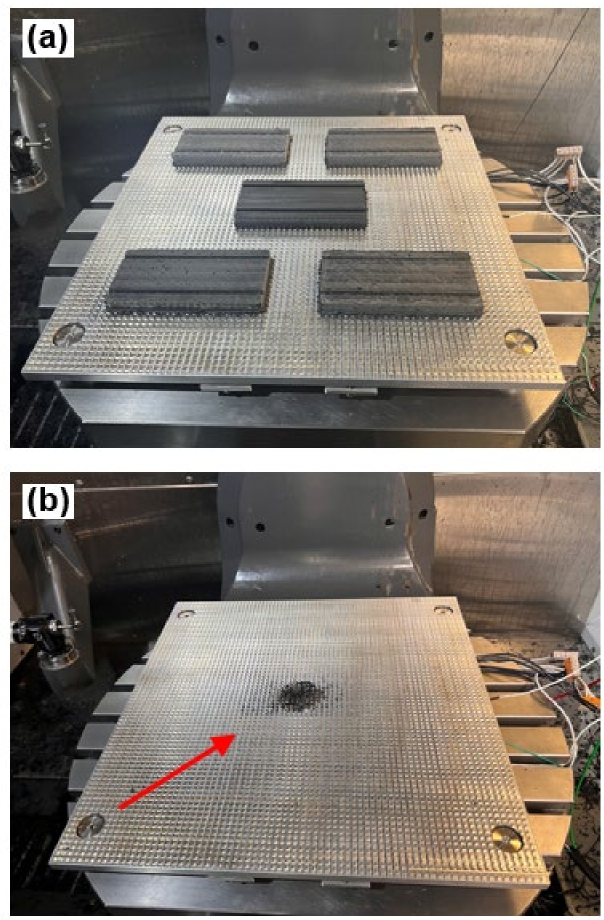

Figure 8. Carbon fiber content was evaluated on the print bed a) after processing and b) after part removal.

To better quantify the bond strength during processing, a modified tensile test was conducted. The three samples resulted in mean stress at failure of 5.9 MPa with a standard deviation of 0.1 MPa. The failure location was through the bulk polymer region on all samples (Figure 9). Because failure occurred in the bulk polymer, an ultimate tensile strength close to that of the bulk material might be expected. However, while previous studies suggest that the ultimate tensile strength of the bulk ABS/20%CF material should be double the value found in this study, they also showed reduced strength at an interface between dissimilar materials [6]. The lower failure stress from this study may be due to the non-standard geometry or the as-printed surface finish. The lower failure stress may also be attributed to the dovetail undercut geometry of the pins allowing for some movement between the polymer and aluminum regions as loading is applied.

The high bond strength presents a potential for this approach to be applied to end-use parts comprised of both metal and polymer. Multi-material parts benefit from local material selection, improving performance through greater design freedom. A demonstration multi-material part consisting of aluminum and ABS/CF regions was produced (Figure 10). Undercut dovetail features with the same specifications as those used on the print bed were nested on the interface metal surface (Figure 10a). The additive system was used to deposit ABS/CF polymer, and machining was used to meet surface finish requirements (Figure 10b). Of course, there is an opportunity to further optimize the undercut geometry for multi-material parts since the goal would be to **permanently** bond the plastic to metal in this use case.

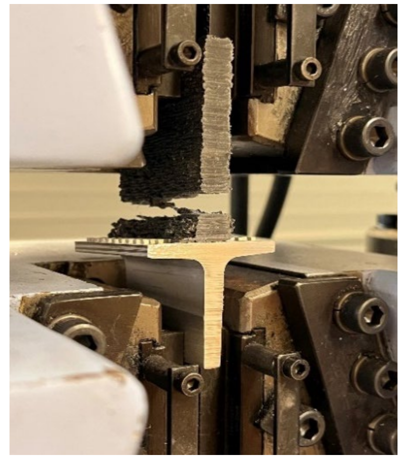

Figure 9. Typical tensile test failure.

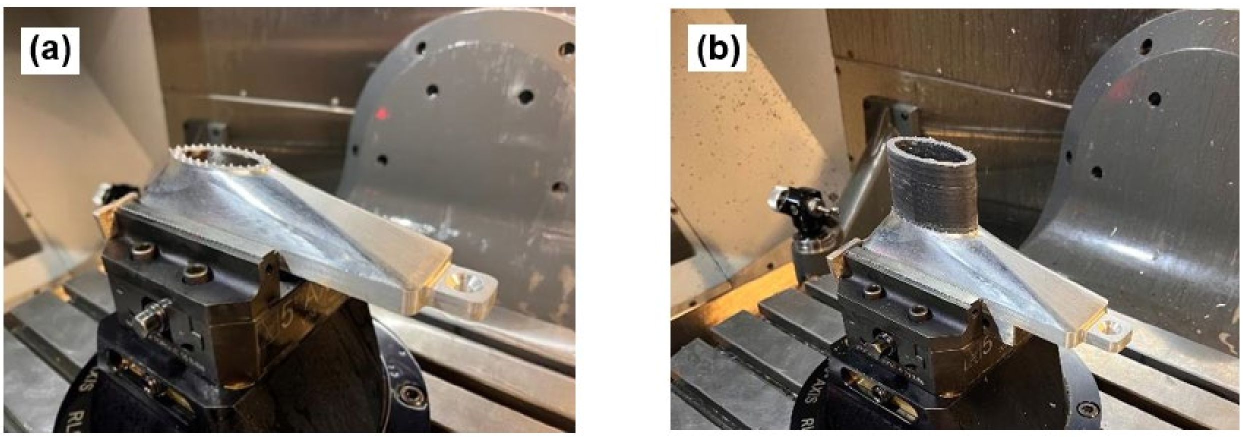

Figure 10. Demonstration end-use part application of the dovetail feature. Processing steps include a) machining undercut features into the interface region in aluminum and b) depositing and machining of ABS/CF blend polymer.

Conclusions

This work presented a novel print bed for large-scale hybrid additive and subtractive manufacturing using a thermally switchable bonding approach. A print bed with mechanically interlocking features demonstrated the ability to meet process requirements for bonding during processing and release the bond when processing is complete. Testing of ABS/CF parts produced with five different levels of chopped carbon fiber content showed that all levels could be effectively printed using the proposed print bed, but samples produced with neat ABS still present some challenges. The concept of the print bed has also shown initial promise in making multi-material parts, where the mechanical interlocking would be optimized for permanent bonding. The improvements made to the build plate can help expand the potential feasible applications for large-scale AM by making the processes more robust and reducing cost.

The proposed method of producing a thermally switchable print bed bond showed the potential for improving the manufacturing process for large-scale AM parts. However, there are still opportunities for refining this method. The size and shape of the undercut pin geometry should be optimized to meet processing requirements while minimizing the removal force and reducing imprints on the bottom of the part. While this study presented preliminary data for the bond strength between the part and the print bed during processing, a more thorough study is needed to understand better how the bond strength is affected by the print bed temperature and the undercut geometry. Scaling this print bed up to a larger scale AM system will uncover additional challenges that need to be solved. The approach of nesting the undercut geometry on an end-use multi-material part consisting of dissimilar materials also warrants further investigation. Mechanically interlocking interfaces can enable the production of tooling and end-use multi-material parts that traditionally are challenging to produce due to dissimilar material characteristics.

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