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Original Publication Citation

Schroeder, A. and Weaver, J. M., "Optimizing Build Plate Adhesion of Polymers in Fused Granule Fabrication Processes," Proc. 33rd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, Solid Freeform Fabrication Symposium.

OPTIMIZING BUILD PLATE ADHESION OF POLYMERS IN FUSED GRANULE FABRICATION PROCESSES

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Abstract

Perhaps the most crucial element of fused granule fabrication (FGF) is material adhesion; in order to achieve a successful product, the material being printed must adhere to the build plate. For optimal products, the material should only adhere to the build plate until the print is complete, then be easily removable. This paper examines the effects of different build plates, environments, and bonding agents on material adhesion during the FGF process in a CNC mill machine. The force to remove polycarbonate (PC) and polypropylene (PP) from build plates was tested with various bonding agents. Except in one case, the adhesive force after the samples cooled was too low to measure; further research is required with a more precise tool to collect more quantitative data.

Background

Perhaps the most crucial element of fused granule fabrication—a subset of additive manufacturing, also known as FGF—is material adhesion; in order to achieve a successful product, the material being printed must adhere to the surface it is being deposited on, whether that surface is the build plate, or bed (in the case of the initial layer), or the layer that was printed previously.[1] With more advanced setups, there could be mold surfaces, channels, and other features that the material will contact while being extruded. For each surface—the build plate, the previous layers of material, and any additional features—the amount of adhesion, or the force it takes to remove the material from that surface, is consequential.[2] For example, the material must adhere to the build plate during the printing process to ensure dimensional accuracy, but it should be easy to remove after the print is complete to avoid damaging the part while it is being separated from the bed.[2] If the part is ever separated from the bed during the print, it often results in failure since the part is liable to shift with the motion of the extruder head and build plate.[1][2][3]

Among the many FGF machines that exist is the Ambit Xtrude, a tool head that can be introduced to large-scale computer numerical control (CNC) mills. Most mills are only capable of subtractive manufacturing—the removal of material to create a product. Introducing the Ambit Xtrude, however, also allows a CNC mill to perform additive manufacturing as well. With this, the machine is capable of printing onto existing structures or different materials after said structures and materials have been machined with subtractive manufacturing. This presents a unique challenge, however, because the structures can have a variety of different shapes based on what prior machining has been done, ergo the print surface may not be uniform or flat. Additionally, the various materials used in the CNC mill have different properties, some of which aren't conducive for FGF.[4] Build surface adhesion is only one step of many needed to achieve successful prints with the Ambit Xtrude, but success in that area literally establishes the foundation for further developments.[1][2]

Among the many polymers which are used for additive manufacturing, polycarbonate (PC) and polypropylene (PP) are two of the more difficult plastics to print.[4] Although both PC and PP present unique difficulties while printing—PC, for example, is incredibly susceptible to moisture and requires high print temperatures (typically greater than 300°C)—they are both prone to deforming as they cool (typically referred to as "warping"), which often results in the part detaching from the build plate.[5] It is for this reason that a heated build plate dramatically improves the likelihood of creating a successful print.[2] However, PC and PP are polar, which can cause issues with build plate adhesion even before warping begins and occurs regardless of the bed temperature.[4] Despite these issues, however, both are widely used in many capacities due to their high strength, heat resistance, and fatigue resistance.[4][6] Thus, it is desirable to achieve consistent methods of printing with PC and PP.

This project aims to evaluate bed adhesion using PC and PP and a large-area additive manufacturing (LAAM) FGF printer, specifically the Ambit Xtrude attachment for CNC mills. Because most CNC mills are not equipped with implements commonly used for desktop printing—namely, a heated build plate; a sterile, debris-free environment; and any form of temperature regulation[2][3][4]—the PC and PP samples were printed onto an unheated sandblasted aluminum sheet to simulate what could be considered a typical CNC environment. Although it is possible to install a heated bed and other devices and systems that can make a CNC machine more conducive to FGF in particular—a prototype bed was constructed as part of this research—the goal of this project is to determine the feasibility of the Ambit Xtrude attachment within a standard CNC environment.

Adhesives for this project were selected that would (1) allow the materials to print successfully, without separating from the build plate during the print or failing in another way; and (2) allow the printed parts to be removed with relative ease, so as to not damage the parts during the removal process. The adhesives selected were the following, due to their low cost, high accessibility, and common use in the 3D-printing community for printing with PC and PP: Elmer's® glue stick; Aqua Net® hairspray; and polypropylene tape, colloquially known as "packing tape."

Although the current scope of the project only aims to evaluate adhesion between PC and PP and the build plate, the data collected should prove useful for determining adhesion with other surfaces as well. Ideally, this research and associated data can be used as a starting point to determine the necessary surface preparations required to achieve the desired level of adhesion to the build plate as far as PC and PP are concerned.

Experimental Setup

Printer Setup

The machine used to collect experimental data was a Haas TM2P CNC Mill with an Ambit Xtrude nozzle. The nozzle was heated to different temperatures determined by the material being printed (either polycarbonate (PC) or polypropylene (PP)), shown in Table 1.

Table 1. Nozzle temperature setting for each printed material. The values used were determined by previous experimentation as well as recommended settings from the nozzle manufacturer.

Material	Nozzle Temperature (°C)
Polycarbonate (PC)	300
Polypropylene (PP)	250

Additives were introduced to the build plate in order to modify the adhesive force between the build plate and the material. A total of 240 samples were printed in the following configurations: 60 samples with no additives, 60 samples with a single layer of Elmer's® glue stick, 60 samples with one coat of Aqua Net® hairspray, and 60 samples with polypropylene tape, colloquially known as packing tape. All of these additives were selected for their common use as adhesives in desktop 3D printing, and more particularly for their use with PC and PP.[5] Half of these samples used PC as the material, and the other half used PP. In between each set of samples, the build plate was cleaned of any residue with water in order to ensure previous samples had no impact on the data.

Table 2. A chart showing the various configurations of test samples. 240 total samples were printed, with 30 samples of each material printed and tested with each configuration.

	Polycarbonate (PC)	Polypropylene (PP)
No additives	30 samples	30 samples
Elmer's® glue stick	30 samples	30 samples
Aqua Net® hairspray	30 samples	30 samples
Polypropylene (packing) tape	30 samples	30 samples

For the tests, a simple sandblasted aluminum plate was used as the build plate. The temperature of the aluminum plate was not manually adjusted and so remained at or near room temperature. This was done to simulate a typical printing environment within a Haas mill, without any special equipment to heat the bed.

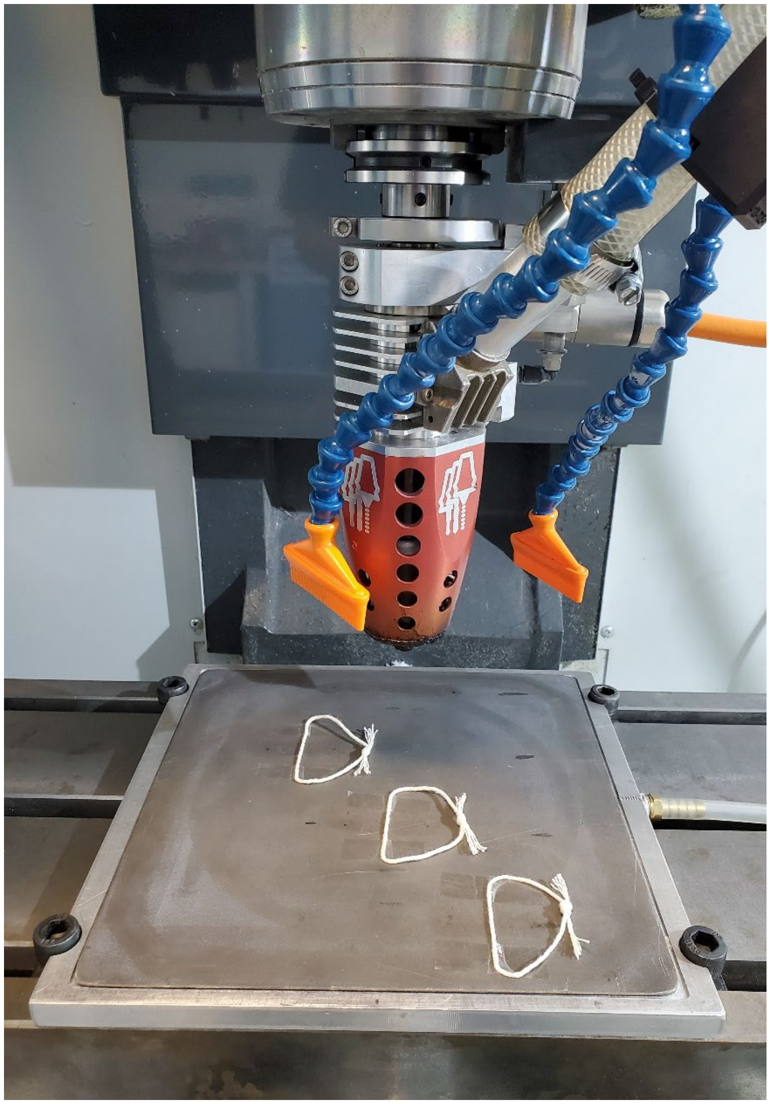

Figure 1. The printer setup inside the Haas mill. Shown is the Ambit Xtrude, mounted in the machine, with the aluminum build plate and string loops for testing.

Data Collection

Polycarbonate (PC) and polypropylene (PP) pellets were extruded into samples, each approximately 3 centimeters long and consisting of two extruded layers. These layers were deposited on the build plate and over a loop of unwaxed cotton string, which was placed in the middle of each sample across its width. The string was chosen for its flexibility and low friction, which kept it from artificially inflating the values and interfering with the data.

After the samples had been printed, the build plate was removed from the Haas TM2P and clamped to a nearby table for testing. The samples were allowed to cool for 5 minutes, at which point a digital spring scale was used to determine the maximum force required to remove each sample from the bed; this was done by inserting the scale's hook through the loop of cotton string and pulling with constantly increasing force until the sample completely separated from the build plate. The maximum value was recorded for each sample and grouped by configuration for analysis and comparison.

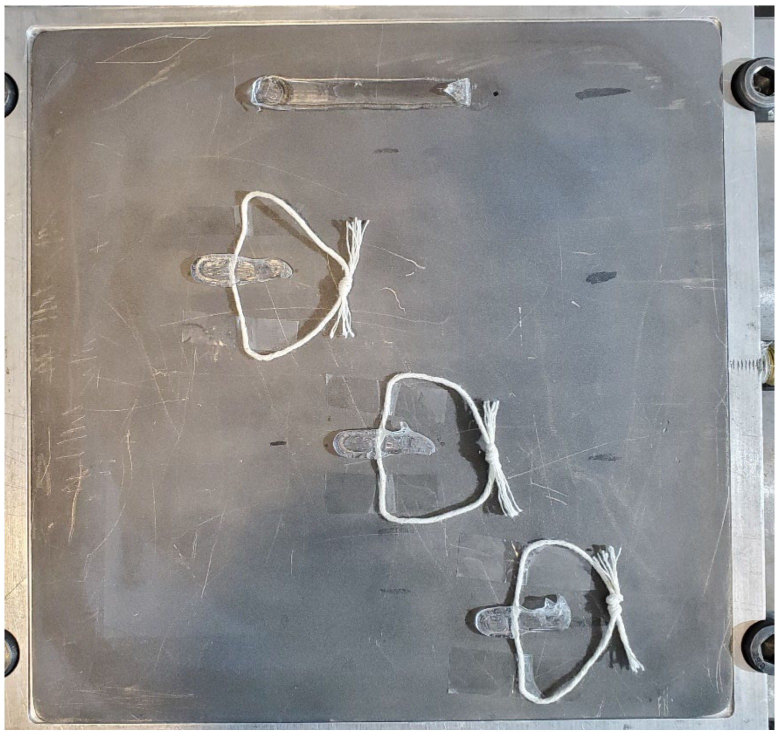

Figure 2. The aluminum build plate and three complete samples after a print. The uppermost strip of material is the purge line, which was made each time to ensure the prints were free of dried material that would otherwise interfere with the results.

<u>Results</u>

Although the samples are of sufficient quantity to be statistically significant, the data they produced is not. Both PC and PP have difficulty adhering to a build plate, especially an unheated one, and the data shows this. Despite the samples printing successfully with the aid of the various adhesives, they failed to adhere to the build plate after cooling, often resulting in values that were too small to be measured. As such, no statistical evaluation can be given for most of the materials and adhesives tested.

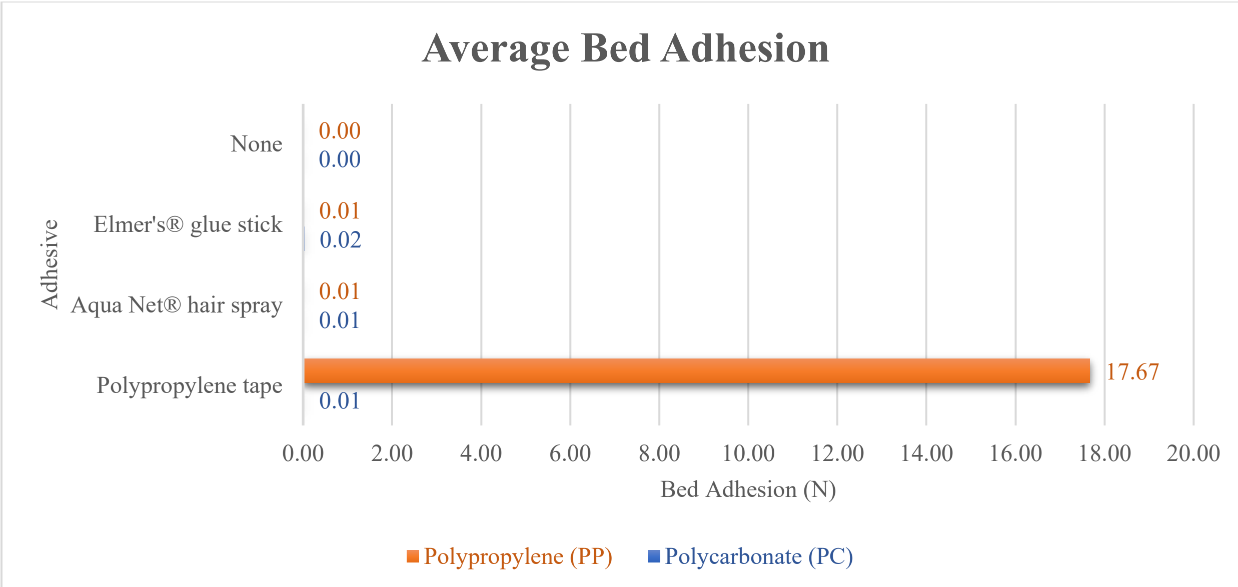

Figure 3. Average bed adhesion from the addition of each adhesive. In most cases, the value is comparatively too small for the bar to be visible.

Polycarbonate

Polycarbonate, as expected, proved difficult to print without the aid of a heated bed or other special features. It failed to adhere to the aluminum build plate without the aid of adhesive, but even when the adhesives were applied, the samples only adhered to the bed for the duration of the print and separated from the bed after cooling. This meant that, although the samples were printed successfully, there is no quantitative data to confirm the adhesives functioned as intended; the data is purely speculative. For some of the adhesives—particularly the Elmer's® glue stick and the polypropylene tape—a spring scale with greater precision may quantify the observed effect, but the number of samples that detached on their own indicate continuous heating is required for continuous adhesion.

Polypropylene

The polypropylene samples functioned almost identically to that of the polycarbonate samples, *i.e.*, the polypropylene failed to adhere to the aluminum plate without assistance, and the other additives maintained adhesion between the bed and the material until the material was allowed to cool, at which point most detached on their own or required less than 0.01 N of force to remove. The one noteworthy exception is the polypropylene packing tape, which created a material-bed adhesion that far exceeded that of any other sample group. This is to be expected since both the additive and the material had the same base polymer (polypropylene). It appears they fused together somewhat when the hot PP was extruded onto the tape, resulting in a stronger bond that took more force to break. The average force for these samples, as shown in Figure 3 above, was 17.67 N and the standard deviation of the values was 5.14 N. It is worth noting that the tape remained firmly adhered to the aluminum build plate and the sample separated from the tape each time, indicating (1) the tape adhesive was stronger than the bond between the PP samples and the polypropylene tape; and (2) the data shows the adhesive force between the sample and the tape, not the tape's adhesion to the print bed.

Discussion and Further Research

As explained previously, polycarbonate and polypropylene were selected due to their utility and difficulty. It is unsurprising therefore that both materials failed to print successfully without the aid of any adhesive and the adhesion between them and the build plate was almost nonexistent after cooling. In the case where the adhesion was significant enough to be consistently measured—namely, the samples of PP printed on polypropylene tape—the adhesion was sufficiently strong to adhere the sample to the print bed after the part had cooled, but not so strong as to impede part removal. This indicates that polypropylene tape is the superior adhesive to use with PP, unless the part being printed is small and low adhesion is desired. The data is inconclusive about which adhesive is preferable for use with PC, and further testing is required with a more precise instrument to obtain quantitative results. The qualitative data, however, indicates that the Elmer's® glue stick was slightly more effective than the other tested adhesives.

As part of this research, a proof of concept was tested that evaluated the feasibility of the adhesives used. For it, larger circular samples—approximately 150mm in diameter and 25mm thick—were printed using a similar setup. The one difference was the scale attached to a small rod that extended vertically to a 15mm-diameter circular base. The sample was printed around this rod and partially on top of the circular base and the spring scale pulled on a hook at the end of the rod to determine the bed-to-sample adhesive force. These tests were too few in number to be statistically significant, but the results demonstrated that the adhesives make a difference. Further testing would be required to prove this idea, but during the testing it was noted that more layers of adhesive increased the adhesion between the build plate and the samples, which presents yet another avenue that can be explored in order to identify the ideal setup for different LAAM FGF print configurations.

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