

Build Plate Design for Extrusion-Based Additive Manufacturing

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Abstract

A fundamental part of machine design for large format polymer extrusion-based additive manufacturing (AM) systems is the substrate where the object is to be constructed, often referred to as the build plate. A good build plate is imperative for a successful build as it is used for supporting and positioning the part during the entire construction. For planar 3D printing, this build plate needs to be flat and in-plane with the X/Y motion of the 3D printer. Additional functionality can include heaters for preventing delamination or warping, vacuum to help prevent warping, removable build surfaces for quick part removal, and mounting features for helping position a part for subtractive operations. This paper reviews existing build plate designs and discusses the design considerations and materials for build plate fabrication.

Keywords: build plate, build surface, extrusion, 3D printer design

Introduction

Extrusion-based additive manufacturing works by depositing material in layers onto a build surface [1-3]. The build surface can be a sheet that sits atop a build plate, or the surface and plate can be the same object in which case the surface would reference the top surface of the plate. Throughout the context of this paper, build surface shall refer to the area where printing occurs and will not be used to reference the entire assembly. The term build plate will be used to refer to a plate supporting the build surface or in reference to the entire assembly in contexts where a separate build surface is not needed.

The build plate and build surface are very important for successful part construction, and without them, the build will likely fail. Properly designed and implemented build plates and surfaces have many characteristics including: good bonding/adherence to the first printed layer, near perfect flatness in-plane with the X/Y motion, and the ability to support the load of the entire printed object.

The build surface is needed to bond and adhere the first layer during the deposition process to lock the build in place [4]. It is imperative that the first layer be printed and captured within the same space for the entire duration of the print. If the material being extruded does not stick on the

first layer, it could drag around the surface and create build-up on the nozzle. This failure to stick on the first layer almost certainly means a failure of the entire build because subsequent layers will not properly adhere and take the correct shape to support future layers. The build surface needs to not only adhere to the first layer during deposition but needs to remain adhered for the entire duration of the print. If the first layer begins to warp or peel away from the build surface, the entire part can become distorted and lose dimensional accuracy. If the entire first layer separates from the build surface, the object may move freely about the build volume and future layers will not adhere correctly causing a failed build. However, at the conclusion of the print, it is desirable for the build surface to easily separate from the part and be reusable for future builds. For thermal-based processes, such as thermoplastic extrusion, this would mean having the build surface adhere to hot plastic and separate easily when cooled.

For traditional 3-axis 3D printing, wherein layers are built in the X/Y plane, then the Z height is advanced to create a new layer, the build surface must be flat and in-plane with the X/Y motion of the system. A non-flat build surface, particularly referring to flatness with respect to the printer's X/Y motion, is very apparent on the first layer because certain areas of the print will stick while low areas may be extruded above the sheet and high areas can cause the nozzle to collide with the surface. Perfect flatness is not a requirement, due to high cost and complexity with maintaining a perfectly flat surface. However, flatness within 25% of the first layer height is desirable. This 25% or less variation in flatness is desirable because small amounts of variation in the surface can be absorbed by the material flow during the extrusion process. After the first layer, if the build surface does not move, the top of the part will be in-plane with the X/Y motion and subsequent layers will be flat with respect to one another.

A proper build plate must also be able to support the load of the part being constructed. With each successive layer that is deposited, the total weight, and thus the total load on the build plate, grows. Modern large format printers can produce objects the size of an automobile with total masses exceeding 1000kg. If the build plate deflects under this load, the top surface of the print may stop being flat and cause adhesion issues for future layers. On larger printers, it is possible for the printed object to become stiffer than the build plate meaning that the warping of the build plate is less obvious at the top layer of the printed object; however, this may create the issue of the build surface and part separating from one another which allows the part to move.

The following sections will review existing designs that are currently available in the marketplace. Then, an analysis will be provided for specific design strategies and aspects of a good build plate.

Review of Existing Designs

Commercially available large and small format extrusion systems offer many different machine configurations and build plate designs with varying functionality including heated vacuum sheet tables, heated and vacuum taped sheet tables, wood board with glued pellets, heated glass sheets, and a variety of off-the-shelf build sheet products such as painters' tape and adhesive sheets. While all these designs have their merits, some may not scale well to large format processes. Each design will be reviewed, and the following section will then take a deeper look at

some of the design strategies at play to understand different means of successfully designing a build plate.

Heated vacuum sheet tables use a build sheet, typically made from a material that will bond well with the printed material [5], as a build surface for securing the part during printing. This type of setup is commonly seen on polymer filament-based extrusion processes where residual stress and warping create small forces that will not overcome the strength of a pneumatic vacuum that is being used to hold the sheet in place. The heat is used to keep the sheet and first few layers of the part warm, ideally at the glass transition temperature (the temperature at which the polymer begins to soften) of the polymer, so that the printed part stays relaxed and flat during the entire duration of the print. A vacuum, typically distributed through a grid in the build plate or a window screen placed on top of the build plate, is used to hold the sheet in place during the print. It is sealed on the outside edges by one large continuous O-ring. The advantage of this approach is the ease of setup. A build sheet can very quickly be placed inside the machine and vacuumed down in place. When the print is complete, the vacuum is released, and the print is removed. A new sheet can quickly be added, and printing can immediately resume. Depending on the sheet and printing materials, sheets can often be reused after a part has been removed. The disadvantages are that prints with a lot of warping and curling can cause the build sheet to lose vacuum during the print and no longer be constrained, the solution does not scale well, and a constant vacuum force is needed for the duration of the build. A large sheet requires a lot of vacuum force to hold it down and is very likely to lose seal at one edge.

Vacuum tables with taped sheets differ from vacuum sheet tables in that they use tape around the build sheet edges to maintain a vacuum seal. This type of setup is commonly used for large format polymer processes where the large prints create high residual stresses and warping. The tape for these setups, usually made from a vinyl-based material, is designed to stretch if the build sheet flexes so that vacuum is still maintained. Often during printing, the residual stress formation will cause the part, and sheet it is attached to, to start warping. Without tape, the sheet may pull away from the vacuum table and thus lose vacuum, leaving it free to continue warping. The tape helps maintain that vacuum seal and allows the vacuum to continue pulling down on the part to help keep it flat. This design requires a vacuum distribution grid to ensure that the vacuum force makes it all the way to the edges, or a vacuum spreader, such as a window screen, to be used so that vacuum force makes it way to the tape. The advantages of this setup are the scalability and reusability. The addition of tape allows for large sheets (upwards of 2 meters on a side) to be held in place on long prints without losing vacuum. Tape also allows for thicker build sheets to be used which are more likely to withstand the print removal process and thus can be reused multiple times. The disadvantages are the labor and material cost involved with applying tape all the way around the sheet as well as the need for a constant vacuum force during printing. Figure 2 shows a Cincinnati Big Area Additive Manufacturing (BAAM) system with an acrylonitrile butadiene styrene (ABS) plastic build sheet taped on the edges and held in place with a vacuum. This system has a single vacuum port and uses a window screen to help diffuse the vacuum.

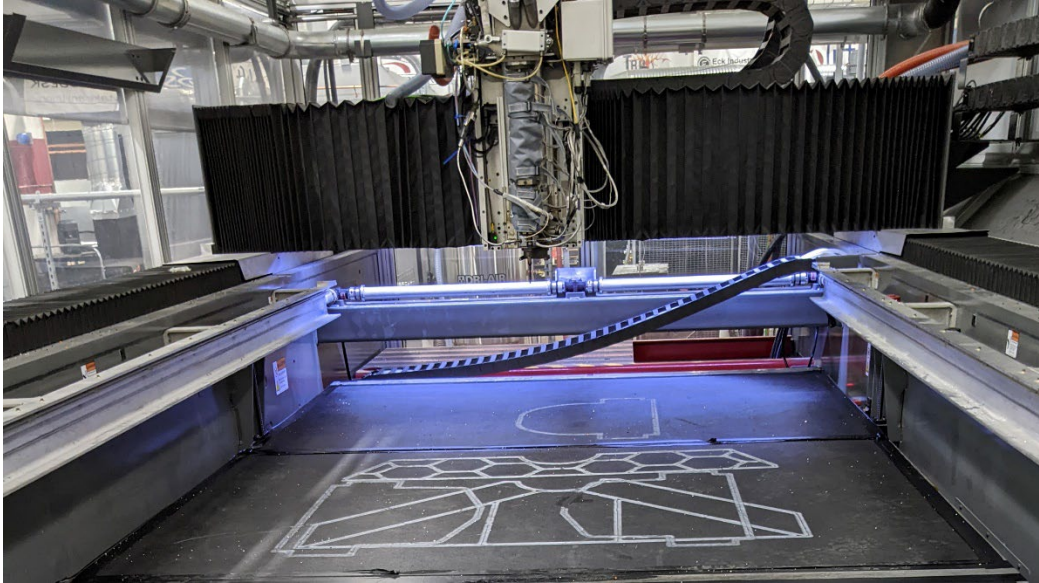


Figure 1: Cincinnati BAAM system with taped build sheets on a vacuum table.

Wood, or other solid surface, with glued pellets is a relatively new solution used by large format polymer processes. The typical setup involves a sheet of medium-density fiberboard (MDF) coated with a mixture of wood glue and polymer pellets. The glue allows the pellets to adhere to the surface for the duration of the print. The pellets are the same polymer that is used for the printing process so that a strong bond is achieved between the pellets and print. The advantages of this setup are that the setup works for large parts and parts can be mounted to the board to prevent warping. Build sheets, like those used for the two previous designs, only come in certain sizes meaning that multiple vacuum tables are needed to hold sheets for large prints. With this setup, an unlimited number of boards can be coated with pellets and set alongside each other. With the build surface being wood based, it's easy to use woodscrews to screw the print into the board during printing to help combat any warping or delamination. The disadvantage of this setup is the cost and time to setup and use a new board before each print. Figure 2 shows the patented bead board approach from Thermwood [6].



Figure 2: Thermwood's version of a wood board with glued pellets, called "bead board" [6]

Heated glass sheets are a simple and low-cost solution ideal for small polymer filament-based extrusion processes. A solid glass sheet, usually made from borosilicate glass because of its improved resistance to cracking at high temperatures, is usually set atop a heated metal build plate and held in place with binder clips or tabs. The polymer can be printed directly on the clean glass when hot, and then easily removed when cool. Not all polymers adhere to the glass on their own, but adhesion can be improved with products such as hairspray, glue sticks, and polymer dissolved in acetone. Commercially adhesion promoters such as Stick Stick and Magigoo are also available. The advantages of this setup are the low cost and simplicity of setting it up. The main disadvantage is the difficulty with getting the print to properly adhere to the glass sheet which is why the market for adhesion promoters exists. However, regular use of an adhesion promoter can lead to a buildup of a glue-like substance on the printer that has to be cleaned away. Another disadvantage is scalability. Glass sheets work well for small parts, but larger parts become too heavy with too much residual stress such that a glass sheet is ineffective. Figure 3 shows a MakerGear M2 printer with a glass build sheet held in place by binder clips.

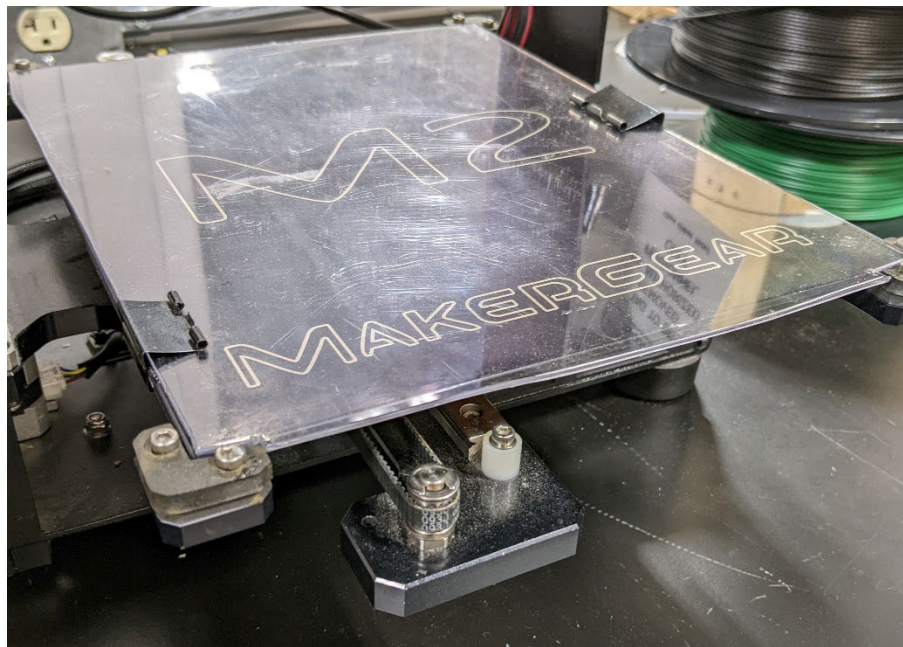


Figure 3: A MakerGear M2 with glass build surface.

A final design is an adhesive sheet or tape on a solid surface that has no vacuum. This setup can be heated, or not heated, and is commonly used for small polymer filament-based extrusion processes. Painters' tape is a cheap and easy to implement solution that can be acquired at most local stores. Strips of the tape are applied directly to the flat surface and printing occurs directly onto the tape. This works well with low temperature materials such as PLA (polylactic acid). For higher temperature materials, and those with a high coefficient of thermal expansion (CTE), which makes warping more likely, special 3D printing sheets can be used. These sheets are typically adhesive backed and can be attached directly to a build plate so that they are fixed in place. Some systems use a magnetically attached flex-steel build plate with an adhesive sheet on top allowing the user to quickly remove and flex the sheet to dislodge the printed part (Figure 4). The coatings

on these sheets are often proprietary, but some simply use a thin layer of polyetherimide (PEI) polymer because of its adhesive properties. Like the heated glass sheet setup, the advantages are low cost and simplicity of setup. The disadvantage is scalability. Large adhesive sheets aren't readily available and may not provide enough hold-down force for materials with a high coefficient of thermal expansion. Flex-steel based implementations don't scale because of the difficulty in removing and flexing such a large heavy sheet.

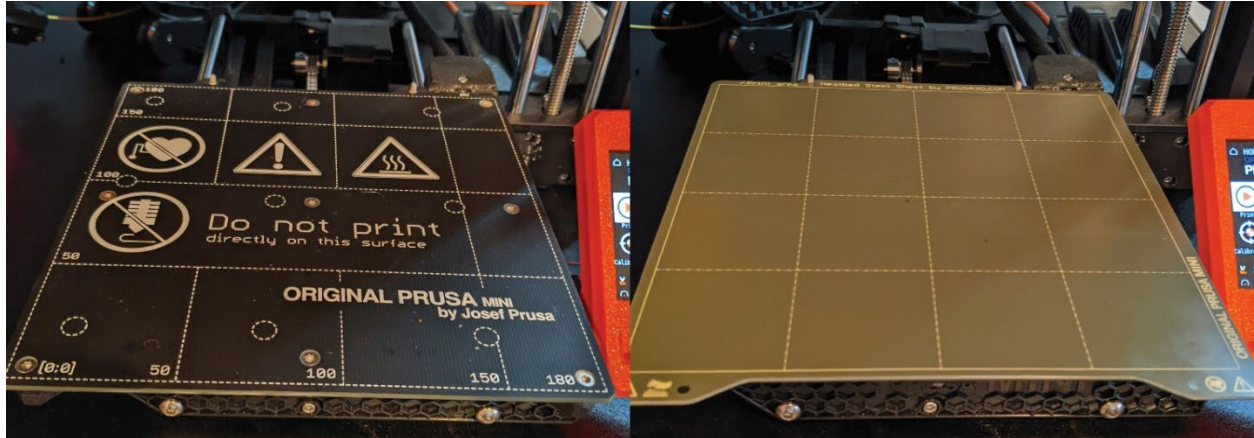


Figure 4: Prusa Mini Build Plate (left) and Prusa Mini Build Sheet (right). In this setup, the build sheet is made from flex steel and coated with a PEI sticker. The build sheet magnetically attaches to the build plate.

Design Strategies

Heated Versus Unheated Build Surfaces

A first major design decision for creating build plates is whether to heat the build surface. A heated build surface is beneficial because the heat helps keep the first layers of the print at an elevated temperature, which prevents the polymer from cooling and contracting which often leads to warping and delamination. Many researchers have proven the benefits of a heated substrate to improve dimensional accuracy, material strength, and print quality [7-10].

The implementation of a heated build surface is similar on both large-format and small-format thermoplastic extrusion AM systems. The most common setup uses single-point temperature feedback for build surface heating, with the build area divided into one or more single-point feedback zones depending on the size of each heater element relative to the build area. Electrical resistive heaters are most common, AC or DC depending on the system scale, with AC systems favored at higher powers due to infrastructure considerations. Common heater designs include silicone-glass composite resistive heaters [11], which are adhered to the underside of the build substrate; and circuit board heaters which incorporate resistive traces directly into a printed circuit board [12,13], which are alternatively adhered to or mechanically clamped against the build surface. It is common for heater underside to be insulated to improve efficiency by reducing heat loss to the environment. In the simplest case the insulation consists of the PCB board itself, larger installations use glass fiber matting or similar insulation.

While many researchers have documented the value and improvements from a heated bed, the unheated bed can still have its merits such as reduced cost. Heating elements for a build surface add cost to the overall system, not just in the cost of the heaters themselves, but in the cost of all the other additional components needed such as heater controllers, wiring, and temperature sensors. For polymer extrusion printers, the heated bed uses as much, or more, power than the rest of the system components combined. There is also the added complexity of integrating the heaters and properly insulating and isolating the heaters from the rest of the system. The heater placement has to be properly designed so that the heat is directed into the build surface and not into the other components of the system, such as motors and drives which are sensitive to heat. If the heaters aren't properly insulated, they will use more electricity to maintain temperature, which will cause the build environment to heat up. A heated chamber is desirable [14], but only if the other system components can handle operation and high ambient temperatures. With all these considerations in mind, it can be beneficial to forego the heated bed whenever the process allows. Low temperature materials, particularly those with a low CTE, can be printed on heated surfaces when the other process parameters are optimized [15].

Design of Vacuum Grooves and Hold-Down Features

As previously mentioned, there are many styles of build plates that use vacuum fixturing, or the process of using a distributed vacuum to hold a build surface or work piece in place during manufacturing. This vacuum arrangement requires a distribution and edge sealing method.

Often the build surface is made of a relatively thin, flexible material such as the ABS build sheets commonly used on BAAM. When only a single vacuum port is used for a flexible sheet, it's possible for the sheet to deform such that a vacuum seal is created around the port hole which prevents vacuum from dispersing to the rest of the sheet. Increasing the number of holes in the plate will increase the area that is being sealed, but the spacing would need to be very close together requiring a large number of holes and additional fittings for the air lines. This is not a very economical solution. With a method of distributing the vacuum, depending on the size, a build plate can use just one vacuum port and still apply adequate suction.

A window screen material or mesh can work well to distribute the vacuum force. It creates tiny gaps between the build surface and the underlying plate to allow the suction to be distributed all the way to the edges. The same goal can be accomplished with a shallow grid, as shown in Figure 5, or pattern machined into the surface of the supporting plate. While it depends on the flexibility of the build surface material, a narrow groove, likely 1x – 3x the thickness of the build surface, can be spaced at approximately 10cm on center in a grid pattern for suctioning down the entire build surface.

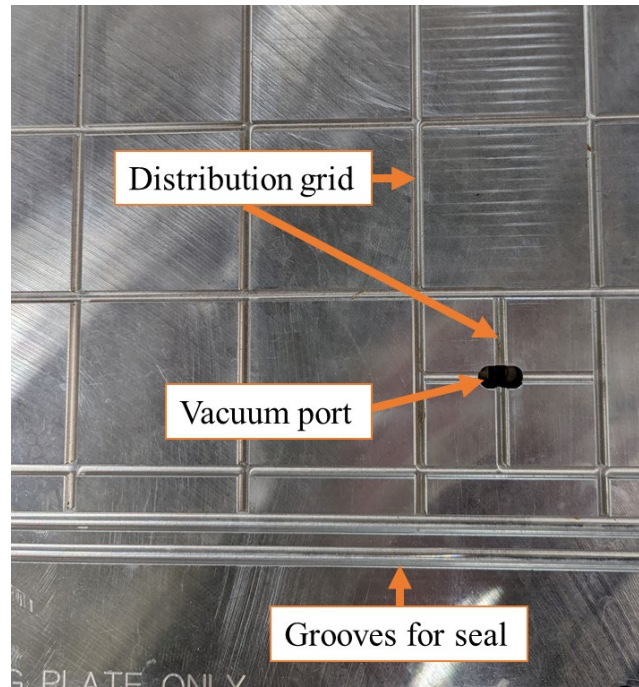


Figure 5: Vacuum distribution system using grid and seal

With either of these methods, the edge needs to be sealed in some way. It was previously discussed that some systems use O-rings to seal the outer edge of the build surface to the plate, but this does not work well for large format systems. Taping the edge of the sheet to the plate works consistently, but the plate must be designed appropriately. To use tape for edge sealing, the grid should not extend all the way to the edge, and there should be space between the edge of the plate and the outer edge of the grid that is smooth and uninterrupted for the tape to stick to. Three centimeters is adequate in most applications. Tall soft closed cell foam seals and flange mounted rubber seals have also been investigated with favorable results. To use these types of seals, a properly sized machined groove to receive the seal is required. This groove should be a closed loop that does not connect to the outside of the plate.

Vacuum fixturing is a well-known method of part fixturing for traditional manufacturing. These systems often see small amounts of side loading and distortion without failure, and the same methodology can be applied to hybrid manufacturing systems if side loading and distortion are minimized. For instances when that is not the case, some additional clamping fixture is necessary. T-slots, shown in Figure 6, are commonly used to fixture parts for machining with toe clamps. These can be added to the edges of the build plate to facilitate the use of bar clamps for holding the part in place.

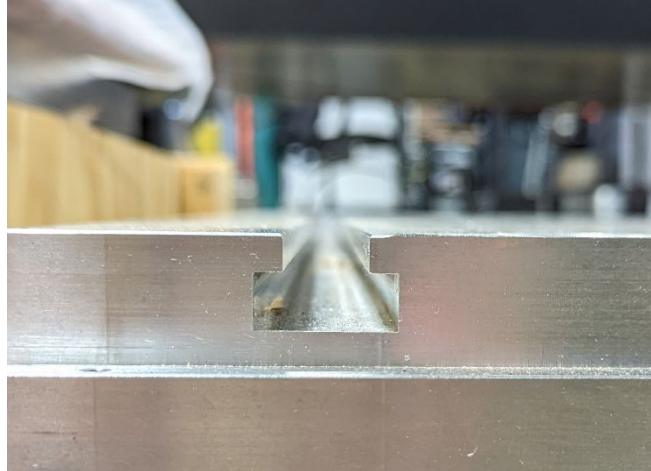


Figure 6: T-slot in build plate for clamping features

Build Plate Material

The material used to make the build plate is another important characteristic that should be considered during design. Desktop-scale systems produce parts on the order of 3kg or less. This reduces the load bearing requirement for the build plate, which is commonly sheet metal [16] or the fiberglass printed circuit board heater, either alone or in conjunction with a rigid build surface such as plate glass [17]. The resulting low thermal mass of the bed assembly may result in temperature nonuniformity across the bed due to natural convection and result in part warping. Solutions incorporating gradient resistive elements throughout the PCB have been developed, to provide additional heat output at the build plate boundary condition [18].

To support the greater mass of parts printed on large-format systems (on the order of 10-1000 kg), build plates are commonly manufactured from metal plate, typically aluminum for a compromise between stiffness, thermal conductivity, and cost. Similar to the desktop-scale printers, electrical heaters can be fixtured to the underside via adhesive or mechanical clamping.

Build plate thickness is dictated by the requirement to provide sufficient stiffness (a function of plate thickness and spacing of underlying support points) while maintaining an approximately uniform temperature distribution within the body of the plate. This is required because the temperature feedback is typically located on the plate underside, immediately adjacent to the heaters, and the print occurs on the topside. For such a lumped-capacitance model to be valid, the Biot number must be kept less than approximately 0.1. This ensures that the temperature feedback provided by the under-bed sensor accurately reflects build surface temperature. The Biot number is defined as $Bi = \frac{h}{k}L$, where h is the convective heat transfer coefficient, k is the body thermal conductivity, and L is the characteristic length of the body, which, in the case of a large plate held at constant temperature on one side, is equal to the plate thickness. The upper limit on build plate thickness at steady-state is therefore $L = 0.1 \frac{k}{h}$, assuming sufficient heater power to hold the heated side of the plate at a constant temperature. Bergman et al. [19] provides a method to estimate the convective heat transfer coefficient of a horizontal plate immersed in air with natural convection. For aluminum ($k_{Al} = 239 \frac{W}{m-K}$) [20], the maximum thickness is 3m, whereas for steel ($k_S = 15 \frac{W}{m-K}$) [21] it is 0.2m. In practice, achieving the lumped parameter condition is trivial, and build plate thickness is commonly on the order of 2.5cm on large format systems. This

design requirement to satisfy the lumped-parameter condition also enables accurate single-point temperature feedback of first layer process temperature if heat is to be drawn out of the part at steady state, e.g. in the case of an exothermic curing reaction in the printed bead.

While metal is the most common build plate material, wood has been implemented on some systems. Wood is a great material because it is readily available, cheap, and does not conduct heat well which prevents it from drawing heat from the part. However, wood does not provide enough stiffness for large and heavy prints, and the poor thermal conductivity also prevents wood from conducting heat from the heating elements to the part. Systems can overcome the stiffness issues by designing a fixed table, making it easier to support on the underside. For lower temperature materials, such as PLA, a heated plate is not required so long as the plate doesn't pull heat away from the part, making a wood plate a good fit for PLA.

Conclusion

A properly designed build plate and build surface are paramount for conducting a successful 3D print. The build surface must adhere to the first layer, maintain flatness within the X/Y plane, and be able to support the load of the full object during the entire printing process. Many different solutions exist in the marketplace today, but there is no one size fits all solution because different processes and machines have different requirements. Certain solutions, such as glass plates and flex steel sheets, do not scale as well as others such as polymer build sheets and vacuum tables. Polymer build sheets typically require heat to promote adhesion which requires a solid support surface that can effectively transfer the heat to the sheet. An effective vacuum table needs to have proper vacuum distribution and room for tape adhesion. Additional features such as a vacuum grooves and T-slot grooves can also be implemented. Further research is needed to improve existing solutions and develop new solutions to keep up with the growing size of 3D printers.

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