Thermal Effects of In-Bed Rapid Prototyping Metastructures

Jeffery L. Norrell, Graduate Student
Kristin L. Wood, Associate Professor
Richard H. Crawford, Associate Professor

Mechanical Engineering Department
The University of Texas at Austin

Abstract

In an effort to produce higher quality Selective Laser Sintering (SLS) parts, a number of approaches have been taken. One such approach is the use of in-bed metastructures, such as tortillas and canisters. In past work, these metastructures have produced changes in part quality, but only qualitative analysis has been done. Using a model created during previous work, a numerical study of these in-bed metastructures is undertaken, with the goal of systematically determining the thermal effectiveness of the various structures. The thermal behavior of in-bed structures subjected to mixed mode convection and conduction is then determined. Results demonstrate that in-bed structures can be designed to *spatially* affect in-bed thermal transfer, providing SLS users the capability to remove or retain heat as a part's local geometry demands.

1 Introduction

Selective Laser Sintering (SLS), a process wherein a laser is rastered across layers of powder in the fabrication of complex 3D parts, is inherently a thermally-based process. Thermal energy in the process drives both local powder consolidation and attachment of a given layer to those layers underneath. With potential SLS part uses including geometrical design visualization, patterns for injection molding, and directly-produced parts, the overall dimensional accuracy of the SLS process is of extreme importance.

In direct conflict with this desire for accurate SLS parts are phenomena including curl, or local part warpage, and growth, or local areas of uncontrolled powder consolidation. Both factors are postulated to be due to lack of thermal control [6, 11].

Through the use of experimentation and numerical simulation [12], we have created a method satisfactory for describing a bulk powder bed's thermal behavior as a function of time and mixed mode heat transfer. But, how might this method be applied to improve SLS part quality through machine, material, or process design?

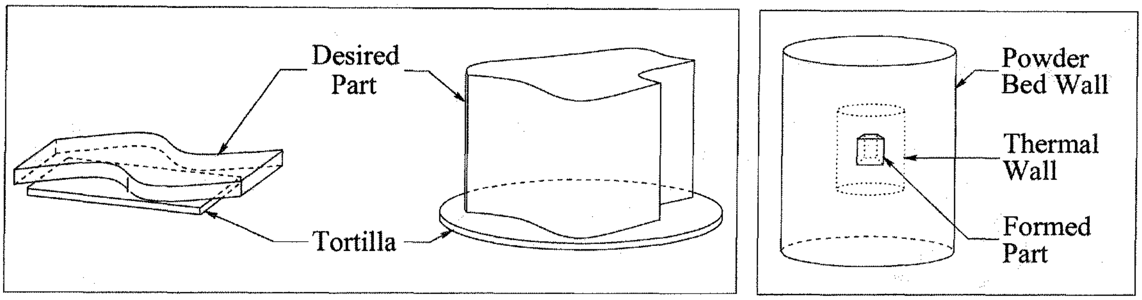
One potential process modification is the use of supplemental in-bed structures, such as tortillas, to alter a bed's behavior. The developed model [13, 14], when applied to in-bed structures, can answer a number of important questions for us. Will tortillas and other structures lead to quicker bed cooldown times, providing a quality increase through higher production rates? Will these "metadevices" hamper thermal transfer out of formed parts, delaying part extraction but potentially reducing the development of in-part stresses, resulting in higher quality parts through increased geometrical accuracy?

In this paper we describe tortillas and other in-bed structures, such as thermal walls. This description is followed by a discussion of parameters governing metastructure usage. An application of the developed model is next, followed by a discussion of in-bed structure parameter sensitivity with respect to affecting a powder bed's thermal state. Finally, we conclude the paper with design recommendations regarding in-bed structure usage and summarize with key points.

2 What is an In-Bed Structure?

In-bed structures are geometry produced during the SLS process, in addition to the part geometry. These structures can come in a variety of shapes and sizes. Shapes range from flat layers to structures completely enclosing a part. These various shapes can be used in different locations within a powder bed, locally modifying a bed's physical properties. Thin in-bed support bases, or "tortillas", located near the bottom of SLS parts have been qualitatively shown to reduce part curl [2]. As well, in-bed structures completely enclosing SLS-formed parts, also known as canisters or containers, have been seen to have an effect on a bed's thermal temperature [3]. Essentially, structures such as containers and tortillas represent methods potentially capable of *spatially* modifying a part bed's mechanical and thermal properties.

Consider the sample systems shown in Figure 1(a). Created prior to fabrication of the desired part, tortillas are thin disks located below a part, typically sintered at a density below that ultimately attainable for a given powder and 20 to 40 layers thick [2]. They are also spaced 10 or 20 layers below a part, where one layer is assumed to be $125\mu m$ thick.



(a) Tortilla examples.

(b) Thermal wall example.

Figure 1: Examples of in-bed structures.

Extending the basic plate-like shapes shown in Figure 1(a), attempts have also been made to expand tortilla usage. Attempted expansions include different shapes and layers supplemented with anchors. As well, in contrast with full layers, simple rings of one or two scan lines below formed parts have also been considered [3].

Extensive in-bed structures are further considered with thermal walls, as shown in Figure 1(b). Essentially, the same notion of a tortilla, or base "wall", is applied along the sides and top of a formed part to supplement any structure fabricated below a part. This thermal wall, completely enclosing a formed part as it is fabricated, is postulated to affect natural convection within a powder bed, thereby limiting thermal transfer from a part and resulting in better part quality from the slower in-bed thermal transfer [3]. Though this effect has not been analytically addressed, brief experiments support this assertion [3].

A logical next step in structure extension is a combination of disks, rings, and walls. A little creativity can result in a very complex arrangement including layers comprised of single discrete scan lines, layers of double scan lines, and layers containing both disks and discrete scan lines. It is believed that this agglomeration of layers forms a barrier, or "wall", beneath an SLS-formed part [3].

A limitless variety of in-bed structures is possible when one considers tortillas or more elaborate in-bed structures. The remaining question, however, is what *exactly* do these structures do for an SLS user?

3 Motivation for the Study

The phenomenon of part curl is commonly thought to be heavily dependent upon a bed's *thermal* behavior [11]. In-bed structures, such as tortillas and thermal walls, have led to qualitative improvements in part quality through the reduction of curl [2, 3]. However, the link between part quality improvement and in-bed structure usage is, at best, only empirically understood. Improvement due to structures may be a consequence of thermal, mechanical, *or* thermomechanical effects. There has been little work addressing which of these physical effects may lead to an in-bed structure's contribution.

However, in-bed structure usage is not without a cost. Powder used in the fabrication of an in-bed structure is powder that cannot be utilized in the creation of an actual part. Time and energy spent creating an in-bed structure directly translates to longer, more costly fabrication procedures. Without an in-depth understanding of in-bed structure effects, balancing the cost of using tortillas with the attained benefit is difficult, if not impossible. This work provides a means with which to evaluate the attainable benefit of in-bed structure use.

The use of our developed model [14] in the consideration of a powder bed modified with in-bed structures can directly lead to a design improvement in this instance, resulting in insights to remedy the unknowns regarding tortilla usage. By examining the significance of in-bed structures through fundamental thermal science, we can directly benefit the SLS process with improved use of in-bed structures. For example, powder usage can be reduced through the use of in-bed structures which have been optimized to provide sufficient benefit while minimizing the expense reflected in used powder.

4 Construction of Thermal Simulation of In-Bed Structures

With the above background and motivation, we now turn our attention to a simulation addressing the issue of metastructure thermal effects. In the application here, let us consider the customer need of a rapid cooldown time [4, 7, 8, 15]. A quicker post-production cooldown will potentially improve the SLS process by reducing cycle times. Such a reduction positively benefits manufacturing throughput of the SLS process. In this section we describe the systems under consideration, the parameters necessary to describe those same systems, and simulation arrangements used to study the systems.

4.1 Representative Systems

We begin by describing a representative SLS system. We consider variables available to describe in-bed structure usage, the in-bed structure material properties, and the process through which in-bed structures are utilized. In this context, we examine the thermal significance of in-bed structures.

4.1.1 Geometry

Consider a cylindrical powder bed approximately 0.43 m (17") deep and 0.25 m (10") in diameter. While current SLS machines utilize rectangular powder beds with these same nominal dimensions [1], a cylindrical bed allows us to exploit symmetry and avoid concerns with corners in the simulation, as shown in Figure 2.

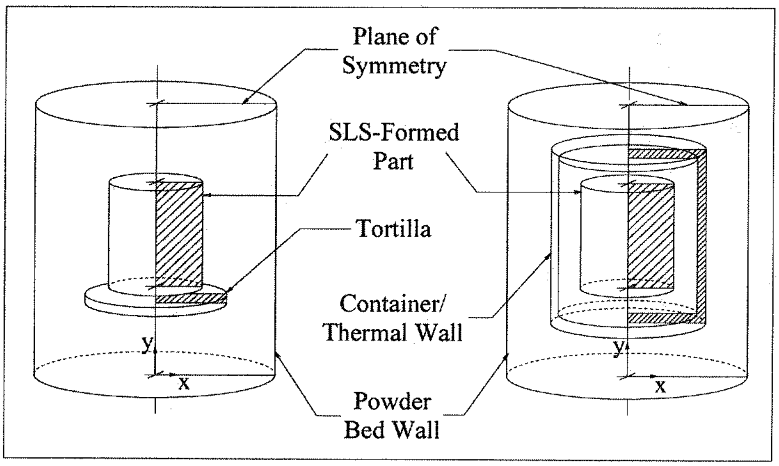


Figure 2: Representative systems, and planes of simulation.

As shown in Figure 2, the plane of symmetry which intersects each powder bed, in-bed structure, and SLS-formed part comprises our modeling domain for this study. Note that the cross-hatched regions in Figure 2 denote areas of "solid" in the symmetry plane, representing both the SLS-formed part and in-bed structure.

Unless being specifically varied, as a starting point in-bed structures are assumed to be approximately 50 layers thick, where one layer is $125\mu m$ in thickness [2]. As well, unless otherwise noted, a spacing of 20 layers is assumed above and below the SLS-formed part.

4.1.2 Material Properties

Along with the given system geometry, we need to characterize the material properties for our system. Bulk powder has a poured porosity of 0.5 [14]. For any part sintered to full density, let us assume a final porosity, ϕ, of 0.01. Assuming such a high degree of sinter ensures no fluid flow occurs through solid parts. Fluid flow through an SLS-formed part is highly dependent upon the part's geometry. The limitless geometrical variety possible in SLS machines makes this an intractable problem with respect to investigating in-bed structure thermal effects. Our assumed low porosity sufficiently scopes our problem.

Let us also initially assume that any in-bed structure, such as a tortilla or thermal wall, achieves a final porosity of 0.25. Such a porosity represents the decrease from an initial porosity of 0.5, driven by the structure being scanned with 40-50% of normal laser intensity [4, 8].

4.1.3 Extended Metastructure

One specific exception to the geometry and material properties discussed here is a more complex in-bed structure arrangement [3], akin to the thermal wall in Figure 1(b) but comprised of a multitude of rings, disk, and plates. In an effort to shed some light upon the results seen with this structure, let us also include this structure in our study.

For simulation purposes, we can calculate effective porosities and determine permeabilities for the thermal wall top, or cap, the thermal wall sides, and the extensive base. The cap is formed of several layers sintered to full density. With a resulting nominal porosity of 0.01, we assume that the cap's permeability, κ, is zero. In essence, it is assumed that no fluid flow will occur through the cap. With a bulk permeability of approximately 10^{-10}m^2 for unsintered powder [14], a permeability of zero for fully sintered powder is an acceptable assumption.

For the thermal wall sides, we have an effective porosity of 0.49. Of particular interest, however, is the *permeability* of the thermal wall sides. As discussed above in Section 2, the thermal wall sides are comprised of 4-ringed structures as shown in Figure 3.

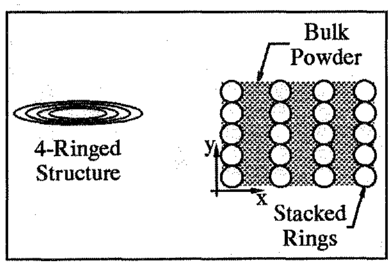


Figure 3: Detail of thermal wall construction for the extensive in-bed structure[3].

While an unintentional feature, the thermal wall morphology results in *anisotropic* permeability. With respect to the coordinate system in Figure 3, permeability in the x direction is essentially zero. In contrast, permeability in the y direction is that of the bulk material. This effect will also be addressed in our simulations.

Lastly, the thermal wall's extensive base has an effective porosity of 0.45 based upon calculating the total sintered volume and its density across all 188 layers. With effectively solid walls, top, and bottom, the base region also has a nominal permeability of zero.

4.2 Operating Parameters

With the system geometries and materials sufficiently characterized, we now turn our attention to the protocol to be simulated. Currently, entire powder beds, or "cakes", are pulled out of SLS machines after a part is formed. These blocks of powder, with the part inside, are then set aside to cool before the formed part can be safely handled. Cool down periods can range up to 24 hours for large parts, for a centerpoint temperature decrease of 393 K (120°C) to 348 K (75°C) [1], where it is deemed safe to remove the part. How will in-bed structures affect this time period?

Let us assume a starting temperature of 393 K (120°C) and a surrounding temperature of 298 K (25°C). We can now numerically examine temperature as a function of time for the case where a cake is removed from an SLS machine and set on a table to cool. Thermal transfer out of the bed is predominantly due to convective heat losses from the bed top and sides, with the table assumed to be an insulative surface. We can contrast this case with one wherein forced convection is used through a bed to enhance the net heat transfer rate.

Note that we use an average powder bed surface convection coefficient, $\bar{h}$, of 1 W/m^2K. With an approximate coefficient of 1.4 W/m^2K, based upon energy conservation for a fluid bath-based wall-heating system [12], and a value of 0.3 W/m^2K based upon flat plate correlations [10], 1 W/m^2K is a good approximate value for our study.

As well, the through-bed fluid velocity arises from previously-examined experimental conditions [12]. With the factorial experiment delineating, over the range tested, a maximum flow rate for improved thermal response of the bed, we opt to use the maximum tested flow rate of 70 SCFH. Note that the velocity of 0.011 m/s is equivalent to 70 SCFH of flow through the larger 0.25 m (10") diameter tube.

Along with these control parameters, we also consider those which are both easily manipulated by an SLS machine's end user *and* independent of a solid part's morphology. For example, varying the type of in-bed structure used only requires modification of appropriate .STL files. In contrast, the amount a tortilla extends beyond a SLS-formed part's edge as shown in Figure 2 is affected by overall part shape and nominal bed dimensions. This dependency makes an exhaustive consideration of the overhang's effect difficult, lending more support to our chosen control variables.

With all of these concerns in mind, we can consider a number of separate simulations to gain insight with respect to various control parameters. Simulations examined include SLS-formed parts with and without tortillas and containers. As well, these arrangements are considered for powder cakes set aside on a table to cool and for powder cakes subject to through-bed forced convection. Lastly, the potential benefit of very extensive in-bed structures [3] are also considered.

5 Simulation Results

With the system geometries and properties sufficiently described and the simulations fully constructed of 9-noded quadratic elements coupled with an implicit backward Euler solver, we can now execute our simulations and examine the results to the mixed convection, transient system. Analysis of the simulation output will offer insight into the overall influence of the various control factors mentioned above.

5.1 Effect of Tortillas and Containers, With and Without Convection

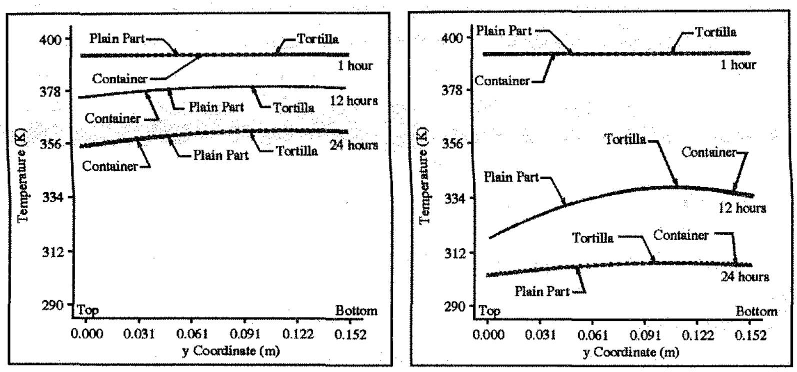
To answer the question of in-bed structure significance, let us examine temperatures along the SLS-formed solid part's centerline. By considering temperature distributions both with and without forced convection and with and without in-bed structures, significant insight can be gained into the effects of forced convection and in-bed structures.

Consider Figure 4(a) where we plot solid centerline temperatures as functions of both time and in-bed structure inclusion for systems without forced convection, analogous to an entire cake being removed from an SLS machine and set aside to cool [1]. Note that, in Figure 4(a), the x-axis' left end is the *top* of the SLS-formed solid while the right end is the bottom.

As shown in Figure 4(a), in-bed structure inclusion has little thermal effect on a system without forced convection. Over a 24 hour time period, there is no significant difference in predicted temperatures, regardless of tortilla or container inclusion.

Is this same trend maintained if we now include forced convection? From consideration of Figure 4(b), we can immediately see that the trend is indeed maintained. There is no significant thermal effect for in-bed structure inclusions *with the parameters considered.*

Note, however, the decided differences between Figures 4(a) and 4(b). In Figure 4(a), even after 12 hours, the center of the solid is at approximately 380 K (107°C). With a target center temperature of 348 K (75°C) for safe handling [1], the simulation predicts that the solid cannot be removed until after 24 hours, which agrees well with previously reported data [1]. With forced convection, this temperature drops to 338 K



(a) Without convection.

(b) With convection.

Figure 4: Comparison of temperatures along SLS-formed part centerlines with and without convection.

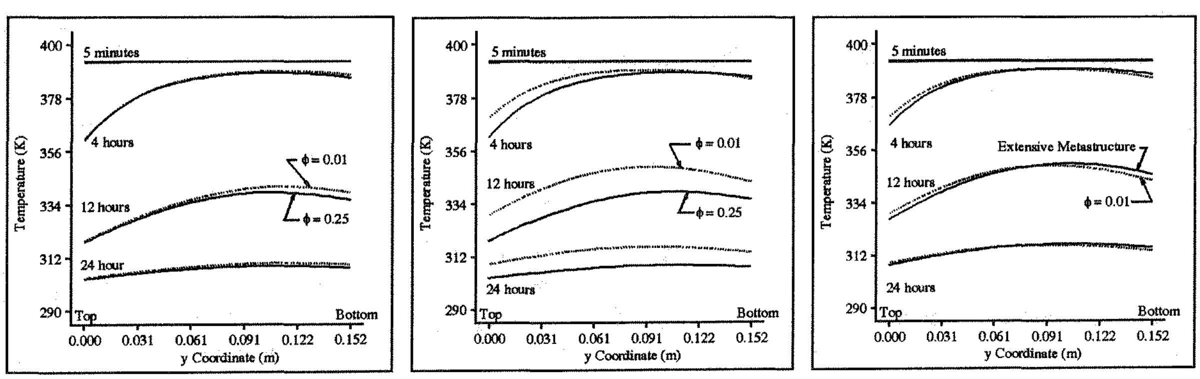
(65°C) at 12 hours, offering a possible remedy to the very real production limitation encountered with part cooldown times. Note that this increased cooling rate comes at the cost of an increased thermal gradient across the solid part, a factor thought to increase curl [2, 5, 11, 15].

It is worthwhile to take a moment and reiterate that the cool down time reduction results are beneficial only if we aim to satisfy the customer need of reducing cool down time as discussed in Section 4. If, instead, our desire is to maintain the thermal energy state of our part in order to delay thermal gradient-induced stresses, then the preferred solution would be to leave a cake sitting on a table to cool.

While forced convection through a cake can have significant effects, there still appears to be little in-bed structure effect at this porosity level. Does a change in metastructure porosity have any effect? Can the relatively simple change of increased sintering for in-bed structures significantly affect temperatures?

5.2 Effect of Varying In-Bed Structure Porosity

Let us begin by considering cake thermal behavior as a function of tortilla porosity in a system subjected to forced convection. From the solid centerline temperatures shown in Figure 5(a), we can see that while there is not a great difference in temperatures within the bed, there is indeed a difference near the bed bottom. The low porosity tortilla (ϕ=0.01) system shows slightly higher temperatures at the solid's base.



(a) Normal and low ϕ tortillas.

(b) Normal and low ϕ containers.

(c) Extensive metastructure[3] and low ϕ container.

Figure 5: Solid centerline temperatures for various in-bed structure porosity configurations.

If we next consider a container with a lower porosity of 0.01, we achieve results as shown in Figure 5(b). The effect of a lower porosity is easily observed, where its use results in higher temperatures within the bed at any given time. In some instances, the temperature is almost 10 K higher within the low porosity container.

The above results are with monolithic in-bed structures, i.e., structures fabricated with uniform porosity. How will an in-bed structure with non-uniform porosity values affect the powder bed's thermal response?

Consider the aforementioned elaborate in-bed structure [3]. As discussed in Section 4.1.3, this structure has nonuniform porosity, nonuniform permeability, and nonuniform thickness. Substantial time is invested in creation of the base with its numerous layers of various construction.

Is all of this process truly required to achieve an increase in bed temperature as seen experimentally [3]? Consider Figure 5(c), which compares solid centerline temperatures at various times for a low porosity container, Section 5.2, and for the extensive metastructure, Section 4.1.3.

As shown in Figure 5(c), there is only a small difference in cake thermal behavior between the low porosity container and the extensive, varying porosity metastructure. However, the small differences that do exist offer insight into the powder bed's overall thermal sensitivity to various parameters.

For the extensive structure, the solid's centerline experiences lower temperatures at the top and higher temperatures at the bottom. Consider that the extensive structure's top is 5 times *thinner* than the low porosity container's top. As well, the metastructure's base is 4 times *thicker* than the low porosity container's base. Essentially, as an in-bed structure's thickness increases, the SLS-formed solid in that region experiences higher temperatures. Conversely, as the in-bed structure's thickness decreases, the SLS-formed part sees lower temperatures.

Lastly, it is interesting to note that, at least from a thermal standpoint, there is no significant reason to utilize the large number of layers and intricate construction as originally described [3]. A container the same thickness on all sides and of a higher density can achieve nearly the same results as a much more complicated structure, as illustrated in Figure 5(c). Given these results, what physical phenomena might lead to an explanation of this behavior?

5.3 Discussion of Effects

With the above work, we observe that container geometry makes little difference unless a lower porosity is utilized. Only at this lower porosity does in-bed structure morphology have an effect. Why does a lower porosity lead to higher in-bed temperatures for a given time?

In actuality, higher in-bed temperatures at a given time can also be viewed as lower porosity beds having a *slower response* to any thermal disturbance to which the bed is subjected. Such a point of view now leads us to consider the change in thermal diffusivity between high and low porosity regions. Given by [9],

$$\alpha = \frac{k_{eff}}{\rho_{eff}\ c_{p,eff}}, \tag{1}$$

thermal diffusivity, α, is a measure of how rapidly a thermal disturbance will propagate through a powder bed. Essentially, the larger α is for a system, the faster a change in temperature will propagate through that system [10].

For our system, when comparing containers at porosities of ϕ equal to 0.01 and 0.25, we have effective diffusivities of $1.25\text{x}10^{-7}\text{m}^2/\text{s}$ and $1.36\text{x}10^{-7}\text{m}^2/\text{s}$, respectively. The decrease in porosity seen with a fully-sintered container results in a 25% decrease in thermal diffusivity. The net result of this effect, combined with the lower permeability seen in low porosity parts, is a slower propagation of thermal disturbances to the solid within a low porosity in-bed structure-modified system.

6 Key Points

From the parameters considered in this study, including tortilla and container usage, structure porosity and geometry, and the use of forced convection, we have gained significant insight into control of SLS-formed part cooldown. With proper choice of parameters, a user can decrease cool down time or maintain a bed's thermal energy level, depending upon their desire. To decrease cool down time, forced convection through a powder bed is mandated. Even at a relatively low flow rate of 70 SCFH, the time for an SLS-formed part to cool down to safe levels can be halved.

Conversely, a low porosity container allows a user to maintain the powder bed's temperature level over a greater length of time. With the potential of thermal gradients within a part leading to post-production curl, containers capable of slowing a part's cooling, and thereby reducing gradient levels, offer much promise.

Functioning due to a combination of lower thermal diffusivity and reduced permeability, instead of a reduction in natural convection, these in-bed containers can be of relatively simple construction. A metastructure comprised of numerous layers of rings and disks in various arrangements does not offer significantly improved control of a bed's thermal state over a simpler, low porosity container.

The important control factors, such as porosity, can also vary spatially. Not only do SLS users have the capability to control an in-bed structure's thickness and porosity, they can modify the thickness and porosity for various sections of the container. Through this approach, a user can affect cooling or thermal retention of a part on a *spatially-dependent* basis. Beds can be equipped with in-bed structures having properties that vary with location. Through such an approach, in-bed structures, near sections of an SLS part with high susceptibility to curl, can be designed with lower porosity and higher thickness. Thermal energy in these curl-sensitive regions can be drawn out more slowly than from other regions of a part.

In conclusion, in-bed structures and forced convection can both be used to significantly affect a bed's cooldown cycle and, in turn, an SLS machine's final part quality, where quality can be measured in parts per hour or final dimensional accuracy. With such process design changes, a user can effectively manipulate cooling from specific regions of SLS-formed parts.

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