Laser Deposition of Metals for Shape Deposition Manufacturing

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Abstract

A laser/powder deposition process has been added to the Shape Deposition Manufacturing system at Stanford University. This process is more robust than previous SDM metal deposition processes, consistently producing fully dense, near-net shape deposits with excellent material properties Material is deposited by scanning the laser across a surface while injecting metallic powders into the melt-pool at the laser focus. A number of parts have been produced with the system, including an injection molding tool, multimaterial structures and simple mechanisms. Currently research is being performed to improve the finish quality of the parts. One of the main areas of research involves controlling thermal stresses which can lead to warpage and delamination. Selective deposition techniques and the use of low coefficient of thermal expansion materials such as INVAR™ show promise for reducing deformations caused by internal stresses.

1. Shape Deposition Manufacturing

Shape Deposition Manufacturing (SDM) is a layered manufacturing technique which uses sequential steps of material deposition and removal to form three dimensional structures. (See Merz *et al.*, 1994 for a detailed description of the process.) In SDM, an off-line process planner first automatically decomposes the CAD solid model of the part into layers and three dimensional sections and generates deposition and cutting paths. Unlike most other Solid Freeform Fabrication (SFF) techniques, SDM retains a three dimensional representation of the part and creates variable layer thicknesses which are dictated by the geometry of the part. Layer boundaries are strategically inserted at heights where there are transitions between undercut and non-undercut surfaces or changes in material. As a result, layer thicknesses will range anywhere from a few thousands of an inch to the practical limits of the deposition and shaping equipment. This adaptive layer splitting reduces build time by reducing the number of layers to the theoretical minimum, and five-axis shaping eliminates the stair-step effect found in other layered manufacturing techniques.

The individual layers are built by depositing material into a near-net shape and subsequently machining it to the final dimensions using a five-axis CNC mill. These operations are alternately performed on part material and additional sacrificial support material. The support material encases each layer, provides a platform for deposition of the next layer, and supports overhanging part geometry. This process is repeated, layer by layer, until the part is complete. After the final layer has been deposited, the support structure is removed to reveal the part in its final, fully-functional state.

Since SDM is a layered manufacturing technique, it exhibits many of the advantages of other SFF processes including the inherent simplicity of building a complex three dimensional shape using a number of simpler individual layers, and access to the interior of the part during the build process. The use of a sacrificial support structure provides other advantages including securely fixturing the part during the build and the ability to produce complex features, such as overhangs and internal cavities. The addition of CNC milling to the process results in part tolerances and surface finishes which are superior to those which would be obtained through a

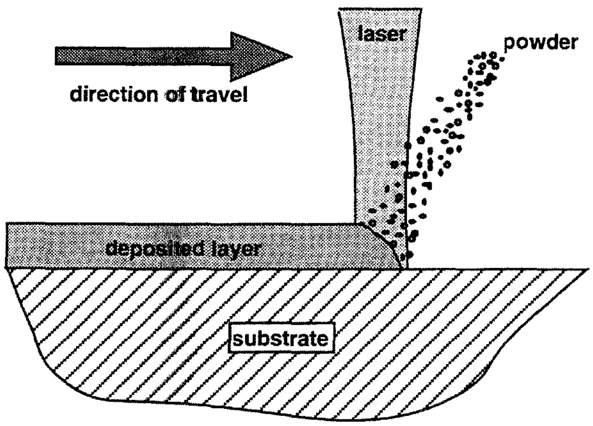

Figure 1: Schematic of laser deposition.

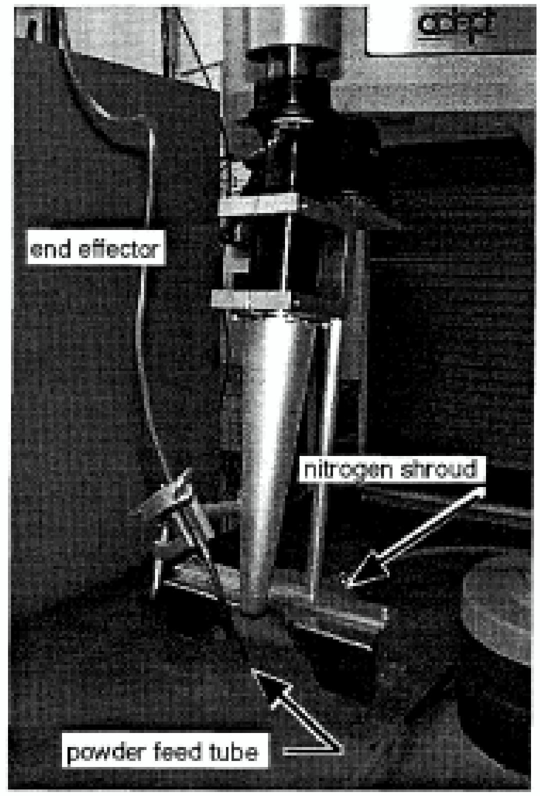

Figure 2: Laser deposition apparatus.

purely additive process. Finally, the wide range of materials available to the SDM process means that fully functional parts can be made in a single, fully automated production step. The technique is sufficiently robust that parts can be made from virtually any machinable material which can be deposited incrementally and for which a suitable support material can be found. Currently the range of materials includes a variety of metals and polymers as well as ceramics in the green state.

2. Laser Deposition System

2.1 System Description

The laser system is one of several metal deposition processes which have been incorporated into SDM. It has a number of advantages over previous SDM deposition techniques including more robust deposition, more accurate placement of the deposited material and the ability to produce functional gradient materials by simply mixing powders during deposition. The process is very similar to laser cladding or laser welding in which the laser forms a melt pool on the substrate into which metal powder is injected. The injected powder fuses onto the substrate as the laser scans over the part, leaving a bead of deposited material in its wake. (Figure 1) Because material is deposited only where the laser strikes the surface and the laser can be positioned accurately, it is easy to selectively deposit material only where necessary and reduce machining time in subsequent processing operations.

The laser is a 2.4 kW CW Nd:YAG laser which is delivered to the focusing optics through a 25 m long, 600 μm diameter fiber. The end of the fiber is equipped with an end effector which can vary the focal length from 130 to 450 mm, with corresponding changes in the focal spot diameter of 1.2 to 4.8 mm. Most artifacts presented in this paper were produced with the substrate approximately 10 mm beyond the focal point and a 2.5 mm spot size. The powders are fed into the melt pool through a simple gravity-driven, off-axis feed nozzle, and the powder feed rates are controlled with an auger-style dry material feeder. Both the laser end effector and the powder feed nozzle are mounted to the end of a four degree of freedom robotic manipulator arm. Since the powder is added directly to the melt pool, the deposition head can move in any direction on the surface. However, the thickness of the deposit does change with direction, with the thickest deposits occurring when the robot travel is in the plane of the laser and powder delivery. The milling operations used in SDM, however, remove any excess material which may be deposited, and control the final thickness of the deposits. During deposition, the area around the laser spot is flooded with inert gas to shield the deposits from air and reduce oxidation. Typically, large flow rates of nitrogen (approx. 150 liters per minute) are used, but smaller flow rates (approx. 15 liters per minute) of Argon or Argon-Helium have also been used successfully. The choice of shield gas largely depends on the material being deposited; for example, the use of nitrogen as a shield gas during titanium deposition could result in formation of unwanted titanium nitride. Figure 2 shows a picture of the deposition apparatus mounted on the robot arm.

2.2 Material Properties

The laser system successfully deposits a range of materials including stainless steel, titanium, INVAR™, aluminum, bronze and a variety of corrosion resistant, hardfacing materials. The majority of the artifacts produced with the system, however, have been made from a material very similar in composition to a 316L series stainless steel. This material has moderate strength and hardness and excellent corrosion resistance. Corrosion resistance is important during the acid etching process which removes the copper support structure. The system reliably deposits approximately 30 g/min of fully dense material into a near net shape. The material properties of the resulting material are very similar to those for a cold worked 316L series stainless steel, as shown in Table 1. Tensile test measurements were taken in two orthogonal directions, parallel to the direction of a single line of deposition and perpendicular to the deposition lines. Visually, the tensile specimens show evidence of some anisotropy in the crystal structure upon fracture, but the material strength is essentially the same for the two directions.

	316L stainless[1]		Deposited stainless	
	annealed	cold finished	parallel	perpendicular
Hardness (Rockwell B)	76	95 max.	90	90
0.2% Yield Strength (MPa)	170	310	490	470
Tensile Strength (MPa)	450	620	630	620

Table 1: Comparison of material properties for deposited stainless steel and standard 316L stainless steel.

3. Artifacts Produced with Laser System

This section will present a few of the parts produced with the laser system including an injection molding tool, multimaterial structures and simple mechanisms. In general these were produced using the laser to deposit the part material and a "microcaster" to deposit the support structure. The microcaster is another SDM metal deposition technique which forms molten droplets above the surface of the part. These droplets then fall and bond to the part (Merz *et al.*, 1994). As a result, less energy is transmitted to the part, and less geometric distortion is observed. The laser system has been used to deposit bronze for support structures, but the laser tends to excessively remelt the substrate and distort the part geometry.

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[1] Material properties for 316L stainless steel from Metals Handbook, Tenth Edition, Vol.1, ASM International, Materials Park, OH, 1990.

Figure 3 shows a photograph of an injection molding tool produced with the laser system. Each half of the tool has dimensions of approximately 152 mm by 102 mm by 32 mm and is made primarily from 316L stainless steel. One half of the tool, shown schematically in Figure 4, has four copper deposits for temperature equilibration. Both halves of the tool have a "U"-shaped channel for water cooling during the molding process. All surfaces of the mold cavity have a 1° taper to facilitate removal of the plastic part. The halves were made in three and five layers respectively, and each required approximately eight hours of automated material deposition and milling. An additional eight hours were required to etch the copper from the cooling channels using nitric acid. Portions of the cavities contained small features which could not be cut with endmills and these were finished with EDM.

Figure 3: Photograph of injection molding tool made with laser system.

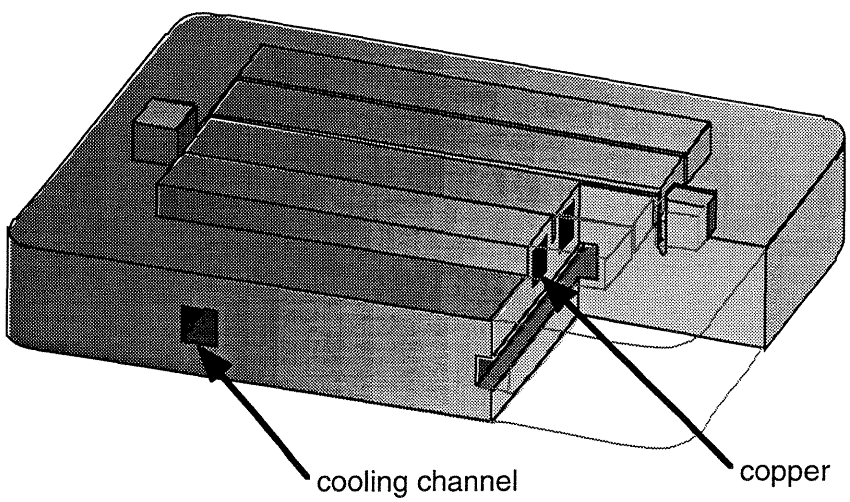
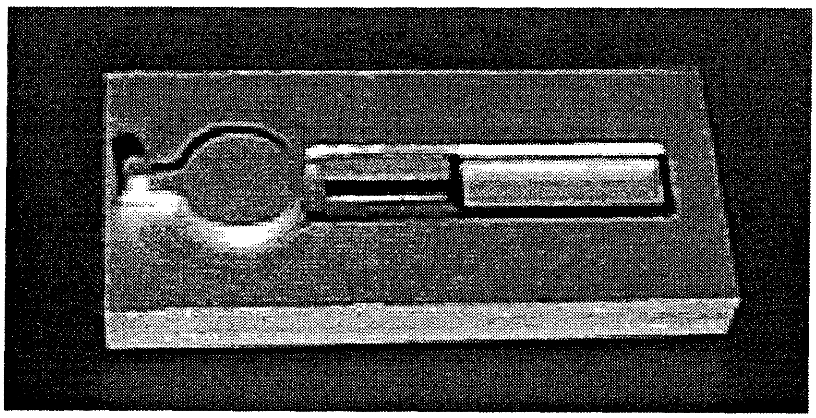


Figure 4: Schematic of half of injection molding tool with copper deposits.

As demonstrated by the copper deposits in the tool described above, SDM can create multimaterial structures. For instance, the laser system has also been used to deposit INVAR™, a low coefficient of thermal expansion (CTE) nickel alloy, onto copper which was previously deposited onto steel. Such multimaterial structures will have significant advantages in a wide variety of applications. In composite forming, for example, the steel substrate would provide a solid base for the die, the copper would serve to equilibrate temperatures and eliminate hot spots in the tool, and the low CTE metal would resist geometry changes due to thermal expansion. The laser system is particularly suitable for producing multimaterial parts because different materials can be continuously alloyed during the build process by simply mixing the powders which are fed to the melt pool.

The laser system has also been used to produce simple assemblies and mechanisms. The use of a sacrificial support structure enables the system to produce a single structure which will become multiple entities once the support structure is removed. For instance, a hollow cube has been made with a sphere trapped inside. A hole much smaller than the diameter of the sphere was drilled into the cube to allow nitric acid to etch away the copper support material and free the sphere. Other assemblies have been made, such as a wheel which spins on a hub and a disk which slides freely in a rectangular frame but cannot be removed. Finally, the system was used to create the simple mechanism shown in Figure 5. In this mechanism, a piston is connected to a crank shaft with a connecting rod. Turning the crank causes the piston to move back and forth in its chamber. This mechanism was made in 12 layers and required approximately 24 hours to fully deposit and shape. An additional 4 hours were required to etch away the support structure.



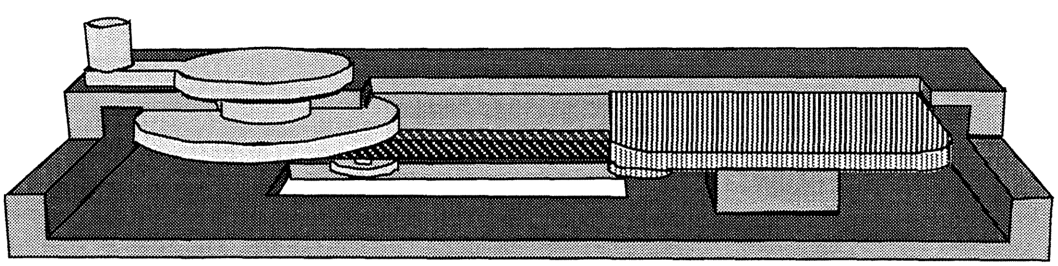


Figure 5: Crank and piston mechanism.

4. Research Issues

4.1 Thermal Stresses

Although a number of artifacts have been successfully produced with the laser system, there are a number of issues, primarily concerned with part quality, which need to be addressed. One of the most important issues which limits the quality of parts produced with SDM is the accumulation of residual thermal stresses. These stresses, which result from fusing and constraining materials of differing temperatures (see Chin *et al.* 1995), can cause warpage, delamination and surface finish defects in the final part. Two primary approaches are being investigated to minimize deformation due to thermal stresses: selective deposition and multimaterial deposition. Selective deposition can reduce deformation of the final part by allowing much of the deformation produced during cooling to occur before the deposit is fully constrained. In this approach the surface area of the deposits is significantly increased by depositing a series of small patches which are later joined together to form large patches of material. These "towers" are only constrained on the bottom and their large surface area to volume ratio allows them to relax significantly as they cool. The individual patches are then "stitched" together to form the solid block. In the second approach, a material such as INVAR™, which has a very low coefficient of thermal expansion (CTE), is used to fill much of the solid center of a part while the outside surface of the part is tailored to the application of interest. For instance, the primarily INVAR™ part may be coated with a thin layer of either wear resistant or corrosion resistant material. The SDM process is suitably robust that multimaterial and selective deposition techniques such as these can be implemented. It should be noted that at high temperatures INVAR™ shows similar thermal expansion characteristics to stainless steel, but at high temperatures the yield strength of both materials is very low. Thus, much of the shrinkage at high temperatures will result in plastic deformation and minimal build-up of internal stresses. At lower temperatures, however, the yield strengths of the materials rise and they build-up internal stresses in accordance with their shrinkage. In this regime, where the stresses accumulate, INVAR™ has a near zero CTE, which results in much lower residual stress levels.

To test the feasibility of these techniques, a series of rectangular beams were produced to measure the relative deflections produced by deposition. In each of the tests, a single layer of material was deposited onto constrained steel substrates. The substrates were 150 mm long, 25 mm wide and 9.5 mm thick low carbon steel flat ground stock. The deposits were milled to a uniform size of 15 mm by 100 mm by 3 mm, and the deflections of the bottom surface were measured. Two deposition techniques, standard and tower, and two materials, stainless steel and INVAR™, were used for this test. The standard deposition technique is a simple continuous scan of the laser across the surface. For the tower technique, individual towers 15 mm long, 4 mm wide and 3 mm tall are built spaced 7.5 mm apart. After the towers cool, material is deposited in the spaces between them to create a solid beam, see Figure 6.

Figure 7 shows the measured deflections of the bottom surface of the steel substrate for several cases. The results show that the deformation of simple beams due to internal stresses can be significantly reduced through both selective deposition and the use of a low CTE material such as INVAR™. The use of INVAR™ reduced the deflections by a factor of 2 as compared to stainless steel. Using the tower deposition technique reduced the deflections by a factor of three. A combination of both INVAR™ and the tower technique reduced the deflections by a factor of 10 over the standard technique with stainless steel. These experiments need to be extended to larger two-dimensional patches and other geometry to see if similar results are obtained.

4.2 Other Research Issues

Aside from thermal stresses, other issues need to be resolved to assure the fabrication of very high quality parts with the laser system. One of the primary issues involves the interactions

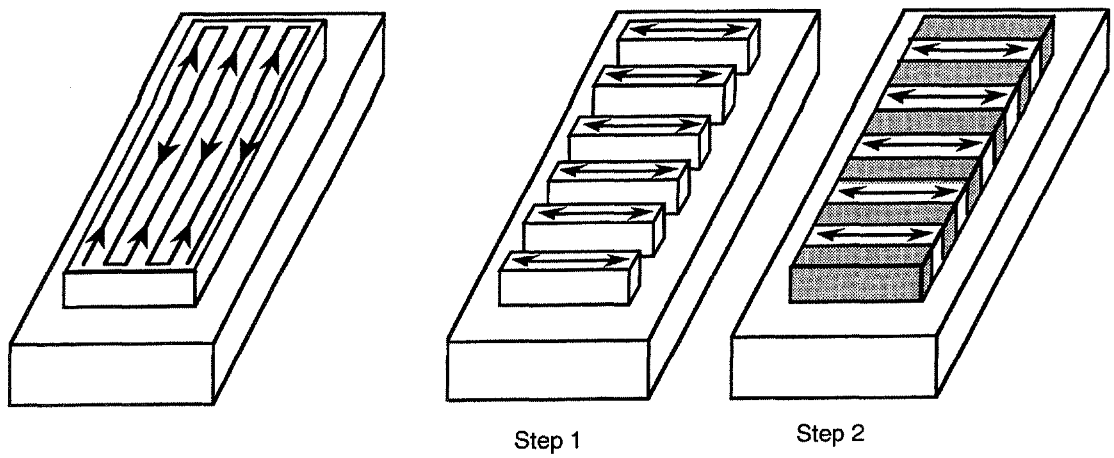


Figure 6: Schematic of two deposition techniques.

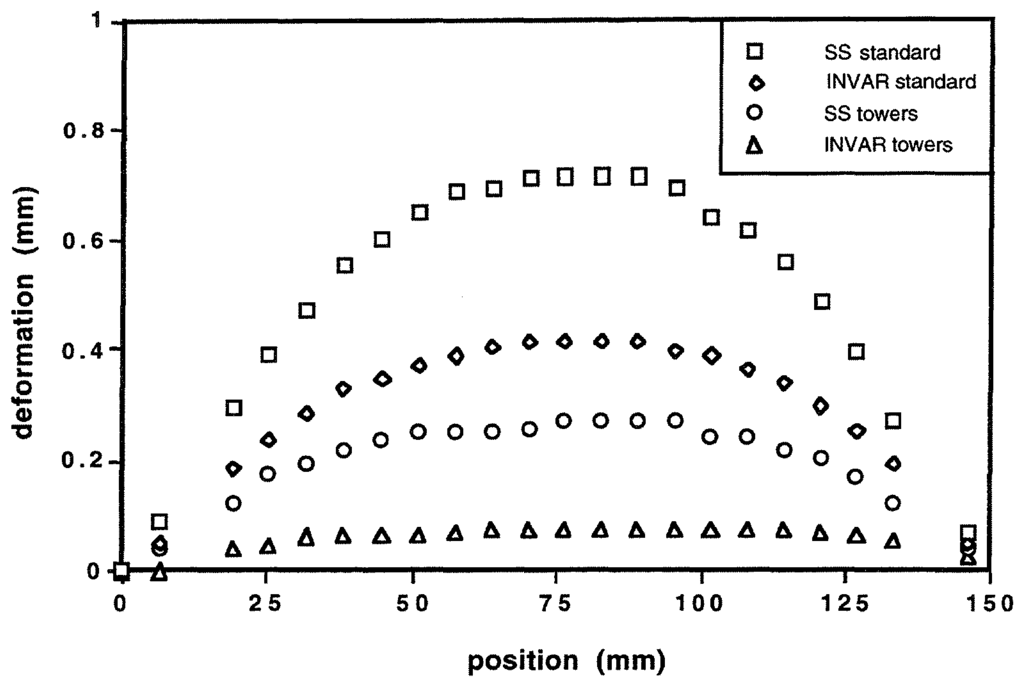


Figure 7: Comparison of standard and selective deposition techniques using stainless steel (SS) and low CTE metal (INVAR)

between the part material and the support material. In SDM one must be able to deposit part and support materials onto one another without destroying the geometry of the underlying material. With the laser system this is not always an easy task because the process requires remelting of the substrate to ensure bonding. Unfortunately this means that if the laser beam hits a sharp corner it will melt the material, and the corner will be rounded as a result. Currently, techniques are under investigation which will coat the support material with a buffer layer which could be melted by the laser without destroying the geometry of the part underneath. Such a buffer layer will be deposited with an alternate technique such as microcasting or thermal spraying which does not substantially remelt the substrate. Such a technique would significantly improve the surface finish of part material which has been deposited directly onto support material.

Another area which has yet to be explored is the possibility of creating functional gradient materials through powder mixing during deposition. A single deposited layer could easily have continuously varying material properties such as hardness or corrosion resistance. This would lead to parts with tough cores and hard surfaces without distinct interfaces between the two materials. Coefficients of thermal expansion could also be selectively chosen to reduce stresses during deposition or control expansion during use.

5. Conclusions

A laser/powder metal deposition process has been incorporated into the SDM system. In principle this technique is a laser cladding process with the goal to build three dimensional structures rather than coat a surface. A variety of metals including stainless steel, bronze, titanium, aluminum and INVAR™ can be deposited in near net shape and then shaped using a five-axis CNC mill. In the process, a melt pool is created on the surface of a part by a 2.4 kW Nd:YAG laser which is delivered fiber optically to the work piece. Powder is added to the pool through a gravity-driven off-axis powder feed system. With the current deposition parameters the system can deposit approximately 30 g of fully dense metal per minute. Testing of the most commonly deposited metal, a 316L stainless steel, shows that the material properties of the deposited metal are similar to those for the bulk material in a cold-formed state. Some anisotropy in the crystal structure has been observed corresponding to the direction of deposition, but this anisotropy does not appear to affect the material strength.

A number of artifacts have been produced using the laser to deposit the part material. These parts illustrate the capability of the system to produce injection molding tools, multimaterial structures and even simple mechanisms. There are still several issues regarding part quality which must be addressed. The first is thermal stresses which accumulate as the part cools and can lead to warpage or delamination. To address this issue, a study is being performed to evaluate the effectiveness of selective deposition patterns and low CTE metals for controlling internal stresses. Preliminary results from beam studies indicate that significant reductions in warpage can be achieved through allowing the material to cool before it is completely constrained and using a low CTE metal such as INVAR™. A combination of the two techniques showed warpage reduction of 90% over the standard case but did increase deposition complexity. The second issue regards the interactions between part material and support material. Good bonding of the deposited layer can only be achieved if the substrate is remelted. This remelting, however, can result in rough surfaces once the support material has been removed. Techniques for nondestructively coating the support material with a buffer layer of the part material are being investigated. Substrate remelting by the laser would be confined to this buffer layer, and the geometry of the support material underneath would be preserved. Continued research in these two area should lead to substantially improved part quality.

Acknowledgements

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