Discrete Multiple Material Selective Laser Sintering (M^2SLS): Experimental Study of Part Processing

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Abstract

Since the introduction of Solid Freeform Fabrication technologies, processing capabilities have evolved to include simultaneous processing of multiple materials in a single component. Selective Laser Sintering (SLS) technology advancement research is being conducted at The University of Texas at Austin to incorporate discrete multiple material processing. Multiple material freeform components are manufactured with material regions separated by discrete or blended (functionally graded) interfaces. An application for discrete M^2SLS processing is found in the production of complex sand core geometries for hollow features in casting. Materials research was performed to identify a support material which burns out during the core firing with little or no residue. A Design of Experiments was performed to determine the effectiveness of electrostatics as a selective powder removal process. Feasibility of producing components by means of discrete M^2SLS was proven through the fabrication of simple geometry tubes.

Introduction

Now that single material processing is thoroughly understood for most solid freeform technologies, the push is toward advancement of these processes to include the processing of multiple materials simultaneously. Multiple material freeform components can be classified as discrete, where material regions are separated by discrete boundaries, or functionally gradient materials (FGM), where the material composition is varied over a distance. Technologies such as Shape Deposition Manufacturing (SDM) and Laser Engineered Net Shaping (LENS) have been successful in producing discrete and FGM multiple material freeform components respectively [1-2]. Processing multiple material components by means of SLS is advantageous over other freeform techniques due to the wide material pool available [3]. Any material that can be obtained in a powder form and is heat-fusible with or without a binder is a potential SLS process material. Materials used in traditional manufacturing processes, such as sand and polystyrene in casting operations for example, are also SLS bulk materials providing the capability to produce fully functional components by indirect or direct methods.

Sand Casting

The traditional process of creating sand casting cores is complex and time consuming. Each internal core is created separately and then assembled by precise gauging. DTM Corporation (now 3D Systems) created a material, Sandform (polymer coated sand particles), which allows the preassembled manufacturing of complex geometry sand casting molds by indirect-SLS manufacturing. A green part is produced by traditional SLS and the green mold is cleared of any support powder from the SLS build. The polymer binder is burned out and the sand particles are sintered during a furnace post fire process.

Unfortunately, a process problem is introduced when cleaning the green part of support powder after SLS processing. Removal of powder from small vent holes (1/4” diameter) often requires excessive handling which can result in fracture of the green mold. One solution to this problem is modification of the current SLS process to incorporate the simultaneous processing of multiple materials in a single build. A secondary material can be utilized as part support during the build which will burn out leaving little to no residue on the mold during furnace firing stage, eliminating the need to handle the part to remove excess Sandform from the green part. Freeform multiple material components can be classified as discrete (material regions are separated by discrete interfaces) or functionally gradient (material blend composition is varied over a distance). A proposed powder delivery method for discrete M^2SLS is discussed below.

Discrete M^2SLS Process

Traditional SLS employs a counter-rotating roller to deliver a uniform layer of a single powder to the part bed. The complication arises in the deposition of multiple powder regions in a single horizontal layer during the automated part build process. There are three general methods to perform the deposition; (1) by depositing a complete layer followed by iterative selective removal and blind deposition of secondary materials, (2) precisely placement of each material in the desired location, or (3) a combination of these two. Our research focuses on the first powder delivery method and is displayed in Figure 1.

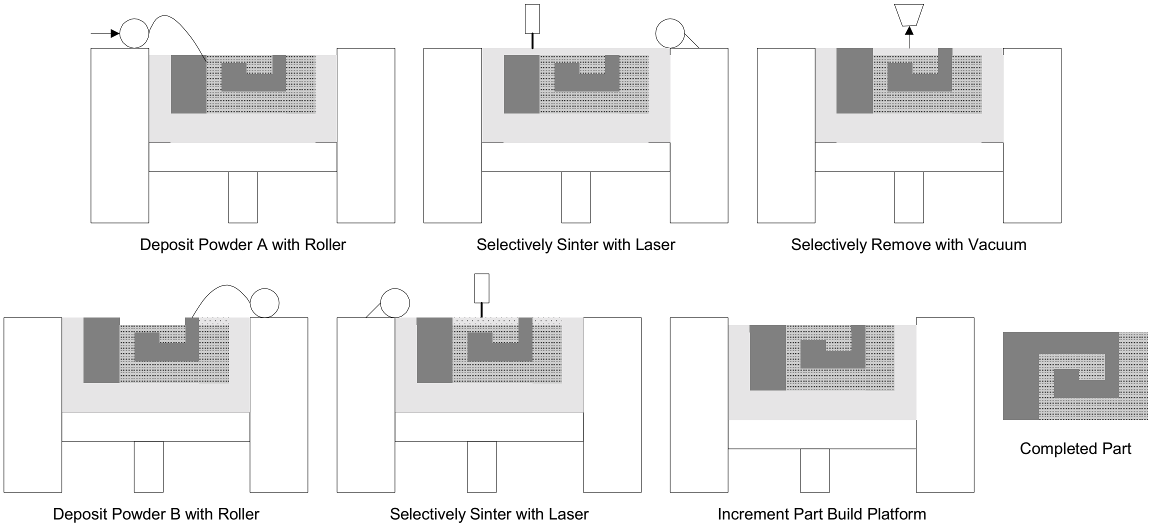


Figure 1: Process schematic for the M^2SLS powder delivery method.

First, a uniform layer of the first desired powder (Sandform in our case) is delivered by a counter-rotating roller as in traditional SLS and the CO_2 laser sinters the powder where desired in the cross-section. The second step is the selective removal of Sandform by vacuum suction to create a void where a region of CastForm PS is desired. Finally, a small amount of powder is placed on the build platform and swept in to place by the roller and sintered where desired. The part bed is lowered and this process is repeated until a complete complex geometry multiple material component is produced. Electrostatic powder removal is investigated as an alternative powder removal method experimentally.

Experimental Setup

Two selective powder removal processes were chosen for comparison during concept selection for the design of a powder delivery subsystem. Both electrostatic and vacuum suction powder removal processes are studied as means of selectively removing powder from the part bed to create a void where a secondary material can be deposited. Electrostatic forces can lift small particles as used in alternate applications such as forensics and laser printers [4-6]. A simple three variable experiment is designed to investigate the volume of powder that can be removed from a powder bed using electrostatic attraction. Similarly, vacuum suction can lift powder to create a void for secondary powder deposition. Simple geometry multi-material components are fabricated in a DTM Sinterstation 2000 using suction to selectively create voids during part build.

Electrostatic Powder Removal

An experiment is performed to determine the effects of three variables on the layer thickness removed from a scaled powder bed using electrostatic attractive force. Figure 2 is a schematic of the experimental setup cross-section. The setup is similar to a parallel plate capacitor with a vertical air gap and loose powder resting on the bottom plate. The upper plate (charge plate) is supplied with an alternating current, while bottom plate was grounded. During a brief charging time (1-5 sec) the loose powder jumps from the bed and adheres to the charge plate. The charge plate is weighed before and after each trial with a Fisher Scientific A-160 balance (0.0001 resolution) to obtain an accurate change in mass. A simple Design of Experiments (DOE), which is discussed below, is used to evaluate the sensitivity of mass removed to each variable.

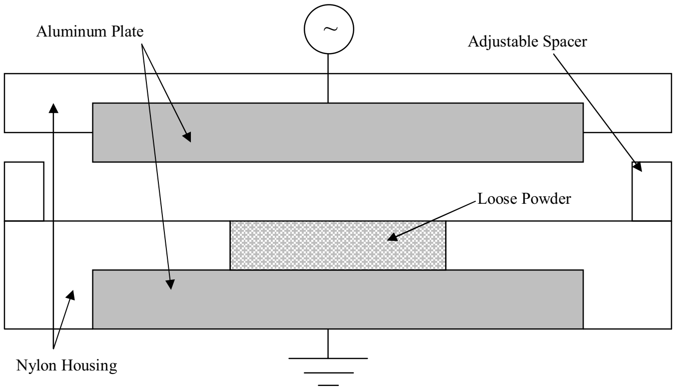


Figure 2: Electrostatic experimental setup cross-section schematic.

Simple Geometry Component Build

Simple geometry components were built in a DTM Sinterstation 2000, pictured in Figure 3. The process steps described in the schematic of Figure 1 were used to build these parts. A separate part build is set up for each material region within a cross section. The process chamber door is opened after each material region is built to manually remove residual powder with vacuum suction and place powder on the build platform to be delivered by the roller. As many as ten layers were built sequentially in each part. Part quality and process issues will be discussed below.

Figure 3: DTM Sinterstation 2000 in the UT SFF Manufacturing Laboratory.

Design of Experiments

The Design of Experiments evaluates the effects of three main electrostatic control variables on the ability to attract loose powder from a particle bed. The performance metric chosen is mass lifted from the powder bed. The three process parameters or design variables investigated were powder removal height, charge voltage and powder material. The design variables and levels used are listed below in Table 1. The control variables, which are kept constant throughout the experimental trials, are the test bed dimensions and testing environment (pressure and temperature). The significant noise variables are the test environment humidity, powder moisture content, residual charge on powder between trials and the particle size distribution. Experimental data and results are presented below.

d_1 : Powder Removal Height (mm)	**d_2 : Charge Voltage (V)**	**d_3 : Powder Material**
$d_1^+ = 4.826$	$d_2^+ = 6750$	d_3^+ = Duraform
$d_1^- = 0.762$	$d_2^- = 2700$	d_3^- = Castform
$\Delta d_1 = 4.064$	$\Delta d_2 = 4050$	

Table 1: Design variables and levels.

Table 2 shown below illustrates the DOE matrix used for the experiments. The trials were randomized to eliminate any bias that could be introduced due to the order in which the experiments were conducted. In addition, the trials were completed in one day to minimize environmental variation noise. The numbers “–1” and “1” indicate the normalized value of the design variable used for that trial, which represent the low and high values respectively. For example, trial number six pertains to a set of d1 = “-1”, d2 = “1” and d3 = “-1”, therefore the experiment was performed with a powder removal height of 0.762 mm, a charge voltage of 6750 V with Castform powder. Table 2 includes the measured values of mass (g) of powder removed from the powder bed in each trial. An initial inspection of the data shows moderate variations between replicates indicating the presence of noise. The results will be discussed in more detail below.

Experiment	Trial #	Mean	d1	d2	d3	d1d2	d1d3	d2d3	d1d2d3	y
3	8	1	-1	-1	-1	1	1	1	-1	0.0204
12	8	1	-1	-1	-1	1	1	1	-1	0.0210
2	7	1	1	-1	-1	-1	-1	1	1	0.0114
4	7	1	1	-1	-1	-1	-1	1	1	0.0106
14	6	1	-1	1	-1	-1	1	-1	1	0.0336
16	6	1	-1	1	-1	-1	1	-1	1	0.0457
6	5	1	1	1	-1	1	-1	-1	-1	0.0789
7	5	1	1	1	-1	1	-1	-1	-1	0.0766
9	4	1	-1	-1	1	1	-1	-1	1	0.0393
15	4	1	-1	-1	1	1	-1	-1	1	0.0395
1	3	1	1	-1	1	-1	1	-1	-1	0.0102
13	3	1	1	-1	1	-1	1	-1	-1	0.0055
5	2	1	-1	1	1	-1	-1	1	-1	0.1121
10	2	1	-1	1	1	-1	-1	1	-1	0.1190
8	1	1	1	1	1	1	1	1	1	0.2510
11	1	1	1	1	1	1	1	1	1	0.1966

Table 2: Design of experiments collected data

An Analysis of Variance (ANOVA) was performed on the collected data. The ANOVA is used to determine sensitivity factors and test their feasibility. This is done by decomposing the total variation observed across experiments into sources of variation [7]. From the feasible coefficients a three-factor linear regression model can be obtained. The general form of the full three-factor linear regression model is:

$$P = \beta_0 + \beta_1 d_1 + \beta_2 d_2 + \beta_3 d_3 + \beta_{12} d_1 d_2 + \beta_{13} d_1 d_3 + \beta_{23} d_2 d_3 + \beta_{123} d_1 d_2 d_3 + error \quad (1)$$

where the β’s are the regression fitting coefficients for each variable and combined effect [8]. Table 3 is a summary of the experimental result from which the regression coefficients are derived.

Trial	Mean	d_1	d_2	d_3	d_1d_2	d_1d_3	d_2d_3	$d_1d_2d_3$	$P_{i,1}$	$P_{i,2}$	$P_{i,avg}$
1	1	1	1	1	1	1	1	1	0.2510	0.1966	0.2238
2	1	-1	1	1	-1	-1	1	-1	0.1121	0.119	0.1156
3	1	1	-1	1	-1	1	-1	-1	0.0102	0.0055	0.0079
4	1	-1	-1	1	1	-1	-1	1	0.0393	0.0395	0.0394
5	1	1	1	-1	1	-1	-1	-1	0.0789	0.0766	0.0778
6	1	-1	1	-1	-1	1	-1	1	0.0336	0.0457	0.0397
7	1	1	-1	-1	-1	-1	1	1	0.0114	0.0106	0.0110
8	1	-1	-1	-1	1	1	1	-1	0.0204	0.021	0.0207
Beta	0.067	0.0131	0.0472	0.0297	0.0234	0.006	0.0258	0.0115			

Table 3: Design of experiments results

Results

ANOVA is also used to test for significance of the mean and each regression coefficient in the general model using the F-test [8]. If the amount of variation of each variable and/or combined effect is high (> 3σ) compared to its effect on powder mass removal, the coefficient will be insignificant and can be eliminated from the general model resulting in a reduced order model. Table 4 gives the ANOVA calculations including the Probability of the F-Test. The terms with F-Test probability values approaching 1.00 are values of high confidence. With 90% confidence a reduced order model is established.

Term	Variable	DOF	SS	MS	F0	P
B_0	mean	1	0.0093	0.0093	46.52	1.00
B_1	d_1	1	0.0028	0.0028	13.89	0.99
B_2	d_2	1	0.0357	0.0357	179.44	1.00
B_3	d_3	1	0.0141	0.0141	70.91	1.00
B_4	d_1d_2	1	0.0088	0.0088	44.24	1.00
B_5	d_1d_3	1	0.0006	0.0006	2.93	0.87
B_6	d_2d_3	1	0.0107	0.0107	53.56	1.00
B_7	$d_1d_2d_3$	1	0.0021	0.0021	10.64	0.99
Total	n/a	16	0.0763	0.0048		
Error	n/a	8	0.0016	0.0002		

Table 4: ANOVA table of statistical results and Probability of F-Test.

The terms associated with the linear regression coefficients determined to be insignificant are eliminated from the general form of the model. These terms do not effect the experimental variation and will have little to no effect on the experimental results [7]. The reduced order terms with high coefficient values are the most sensitive to small variations in the corresponding experimental terms. The performance of the electrostatic removal of loose powder from the test bed is affected most dramatically by change in applied charge voltage. Only the coupled coefficient β_{13} was deemed insignificant, therefore the remaining terms are included in the reduced order model, shown below.

$$P = 0.067 + 0.0131d_1 + 0.0472d_2 + 0.0297d_3 + 0.0234d_1d_2 + 0.0258d_2d_3 + 0.0115d_1d_2d_3 \quad (2)$$

Figure 4 illustrates two simple geometry components manufactured by M^2SLS with vacuum suction used for the selective powder removal method. The components each consist of a solid Sandform base built in a traditional SLS automated build topped with several multi-material (Sandform and Castform) layers built manually as discussed above. These parts were successfully produced after several manufacturing attempts and process parameter variations. Several process issues arose due to the inconsistent environment while opening and closing the chamber door during the manual build of the multiple material layers. These process and additional materials research issues are discussed below.

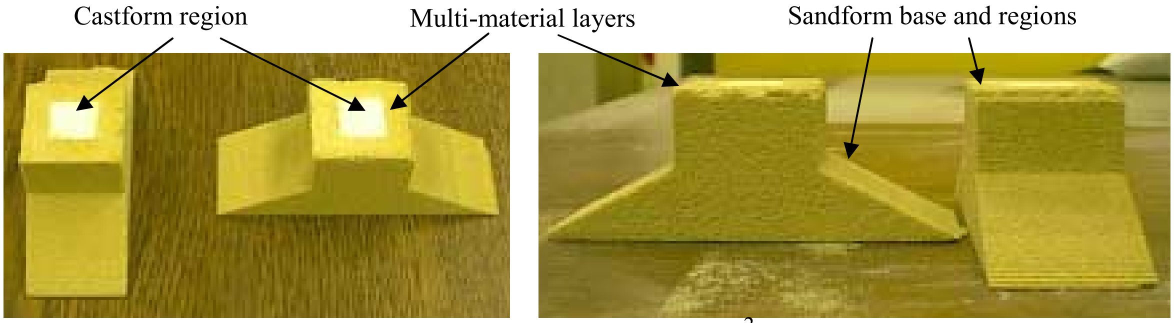
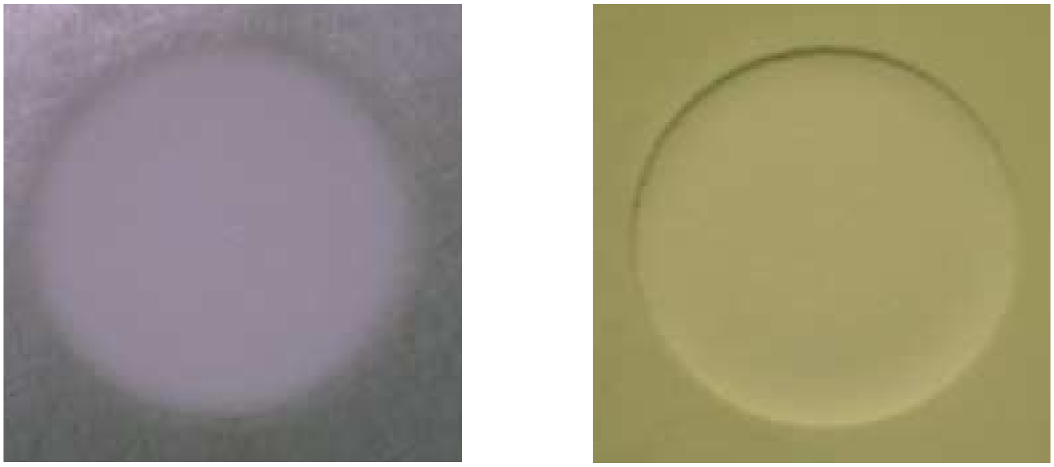


Figure 4: Simple geometry components built with M^2SLS using vacuum suction.

Discussion

The result of the DOE produced several important insights into the removal of loose powder from a particle bed by means of electrostatic attraction. Results showed that although significant amounts of powder were removed by electrostatic force, the removal patterns were inconsistent between trials. The objective of the experiment was to determine if the depth of the powder removed from the test bed can be controlled within the window of deposited layer thickness of traditional SLS, 0.004”-0.015”. When accounting for the density and loose packed volume of the powders removed, minimum and maximum depths removed were 0.0008” and 0.0239” respectively. One combination of test parameters gave a promising result. The trial five parameter combination (“1”, “1”, “-1”) resulted in the most uniform powder removal from the test bed. Figure 5 demonstrates this pattern. These results in conjunction with a successful part build show promise for the potential to build discrete multi-material freeform powders from a wide range of material with SLS. Unexpected experimental results were observed during electrostatic removal of powders and manual build of simple geometry components.

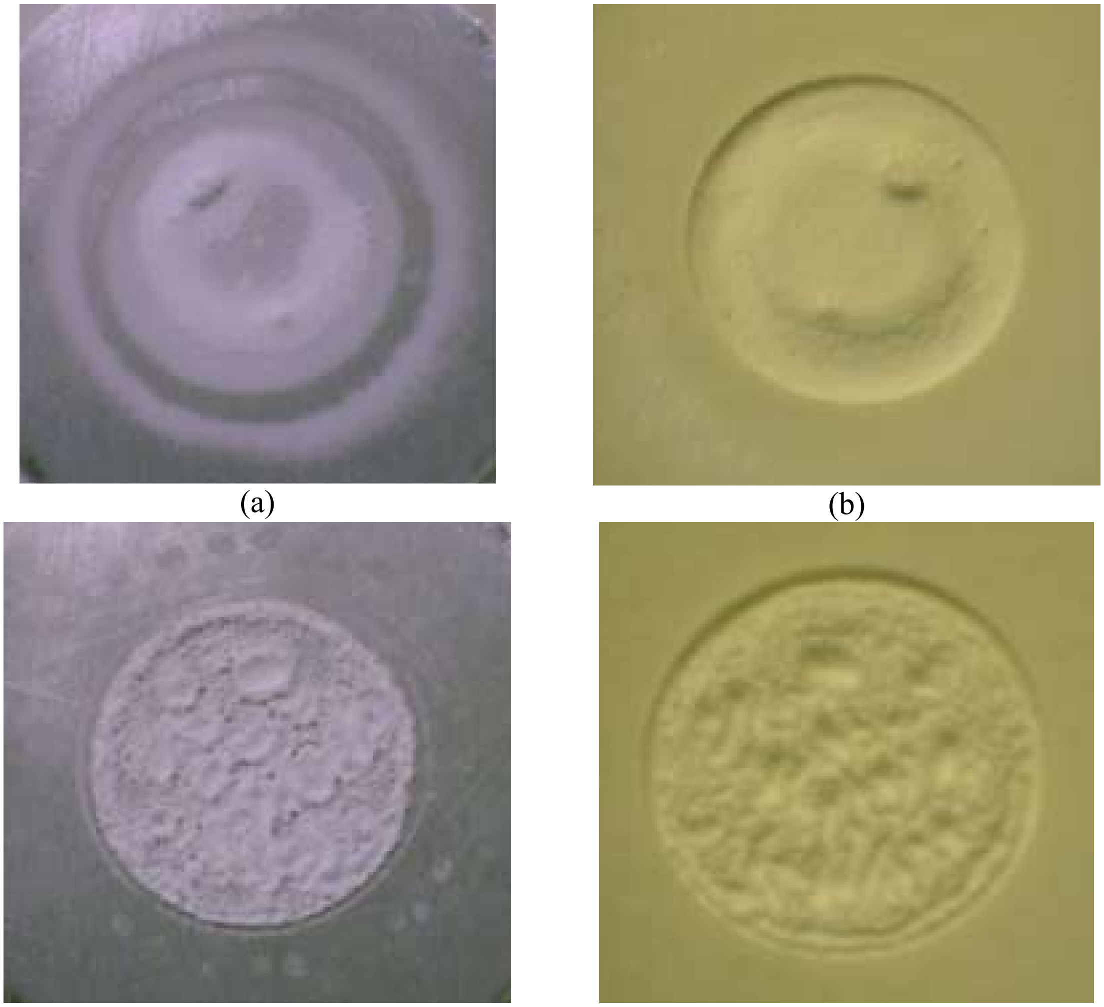


(a) (b)

Figure 5: Trial 5 powder removal pattern (a) powder collected on the charge plate and (b) remaining powder in test bed.

Several trial parameter configurations result in inconsistent powder removal. The parameter combination of Trial 6 ("-1", "1", "-1") causes the powder to build in isolated locations, which in time build bridges between the powder bed and charge plate. This creates a connective path, preventing the charge from distributing uniformly on the plate. This can be caused by imperfections on the surfaces of the charge plate or the powder bed. A halo formed around the perimeter of the powder bed opening signifying a build up of charge around the rim of the bed. Another interesting effect is the appearance of a snake-like pattern in the attracted powder and bed as produced by the Trial 2 ("-1", "1", "1") parameter combination. During experimental testing under these conditions discharge sparks were seen between the charge plate and powder surface. The attracted and remaining powder patterns are pictured in Figure 6. While the mass of the powder removed under these parameter combinations is significant, the patterns are nonuniform. This leads to excessive powder removal in regions while insufficient powder removal in the remaining regions. Considering the goal is to remove a uniform layer of powder from a bulk powder bed, these results are undesirable.

While the experimental results show promise for the use of electrostatic attraction as a selective powder removal method, there is the presence of inconsistent performance. The ANOVA revealed all but one regression coefficient to be significant to the mass of powder removed from the powder test bed. This implies that the error in the model is low. Although this is desired, the inconsistent powder removal patterns prove the complexity of a system using this technology. The challenge of using electrostatics is only expected to increase when incorporating process parameters as seen in SLS. Other powder removal methods will be evaluated before the further investigation of electrostatics as the primary means.


(a) (b)

(c) (d)

Figure 6: Undesired powder removal pattern (a) trial 6 attracted powder pattern, (b) trial 6 powder remaining in test bed, (c) trial 2 attracted powder pattern, and (d) trial 2 powder remaining in test bed.

Process Issues

During the simple geometry part fabrications several process issues arose. SLS powders require elevated build chamber temperatures for optimal sintering. Optimal powder sintering is achieved during SLS by elevating the temperature of the powder to just below the powder (direct SLS) or binder (indirect-SLS) and supplying energy to surpass the melt threshold with a laser [9]. Some powders require additional build environmental controls such as an inert atmosphere to prevent oxidation. The manual multi-material powder delivery requires the chamber to be opened between material regions. Disrupting the chamber environmental equilibrium, especially process temperatures, inhibits the part build. Incomplete interlayer fusion was seen in the layers built manually. Figure 7(a) displays layers flaking away around the edges of a multi-material cross-section.

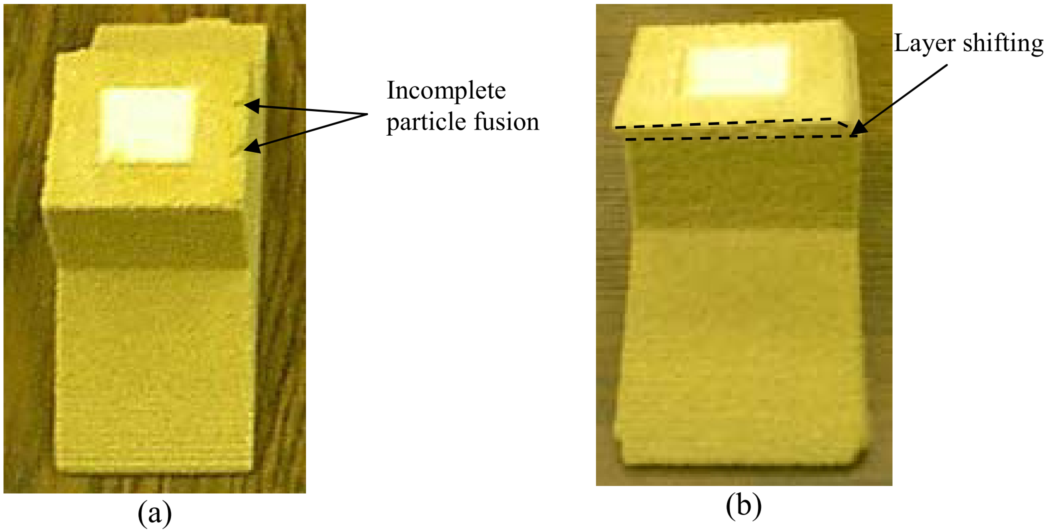


Figure 7: M^2SLS process issues; (a) interlayer delamination or incomplete powder adhesion and (b) layer shifting of multiple material layers.

The mechanical delivery of the second powder by a roller caused two problems. Initially the part bed piston was left even with the build platform for delivery of the Castform. As the roller delivers the Castform to fill the void region layer shifting occurs when the roller collided with the part. This was compensated by lowering the piston below the level height to allow sufficient clearance between the part surface and the roller. Misalignment of the two material regions within the cross-section results, which causes part dimension in accuracy. The second problem is material cross-contamination. As the roller delivers the Castform it is rolled over the entire exposed part surface and part bed. Residual Castform is left on the surface outside the desired deposition area and intermixes with the unsintered Sandform in the bed. The Castform can add to the problem of incomplete fusion between consecutive Sandform layers and possibly contribute to delamination. Figure 8 displays the desired Castform deposition area and the evidence of powder outside this region. The upper layers of this part delaminated at the interlayer boundary.

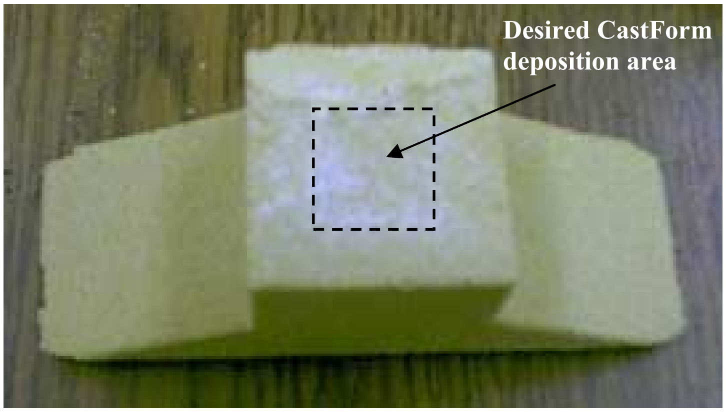


Figure 8: Cross-contamination of the SandForm region with CastForm outside the desired deposition region.

Future Work

The successful simple geometry discrete M^{2}SLS component part build encourages the research effort for SLS technology advancement here at The University of Texas at Austin. The induced process issues encountered during investigation of electrostatics and vacuum selective powder removal techniques reveals the need for further design efforts. The delivery method used in this experiment, although traditional SLS process and machine changes are minimized, induced further process issues that must be alleviated for Discrete M^{2}SLS to be commercially successful. Design methodology will be applied to investigate design alternatives. Further experimentation will be performed to test the feasibility of precision rather than selective powder delivery subsystems.

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