Small Size Fluidic Devices by Freeform Manufacturing

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Keywords
freeform manufacturing, selective laser sintering, in-line static mixer

Abstract

The objective of this study was to innovatively use Freeform Manufacturing, specifically Selective Laser Sintering (SLS) to fabricate rapid prototypes of small size fluidic devices. The polymer used by the SLS application is very porous and presents a rough final surface. Material analyses were performed using Scanning Electron Microscopy (SEM), optical microscopy and Rockwell P hardness tests to develop methods for physical property enhancements. The study showed the feasibility of manufacturing a functional miniature size, e.g. sub-centimeter size, in-line static mixer derived from available macro-scale models using SLS and an additional coating process. It was determined that some of the variable parameters of the SLS process affected the mechanical and physical properties of sintered specimens. Related issues can be enhanced by sintering at relatively high laser power settings and post-processing the prototype with a polymer based coating.

1. Introduction

Industry has been continually changing techniques to produce mechanical work. Fluidic systems can be used to replace electrical systems in demanding applications for which they are not efficient. Already there are fluidic systems applications such as microanalysis systems, drug delivery devices, diagnostic tests, and fluidic biosensors. In this context, this study proposes manufacturing in-line static mixers by more automated means that can fit today's industries growing technological and economical needs. In-line static mixers are fluidic devices used in many applications such as drug delivery, food processing, pharmaceutical industry, toxic waste treatment, and water processing.

Solid freeform manufacturing, or freeform manufacturing (FFM), is a revolutionary technology used in building functional parts that can substitute production-quality parts[1,2]. This technology can automatically construct layer-by-layer physical models from computer-aided design (CAD) data. FFM involves many specific processes that take different names, and they are also often used as synonyms for the entire field of rapid prototyping. Selective Laser Sintering (SLS) was the manufacturing technique of choice for this project. Since the presented layer-by-layer manufacturing concepts and methods work for SLS, this feasibility can be expanded to many other FFM technologies

1.1 Materials and Technology Limitations

This project used EOS™ polyamide 2200 (PA) (Nylon 12), a material widely used in SLS applications. EOS™ PA has been developed specifically for creating rugged engineering thermoplastic parts that withstand aggressive functional test-

ing. EOS™ PA, however, has properties that may not be ideal for the manufacturing of functional prototypes of small size devices (i.e., porosity, surface roughness, low tensile strength). Currently, SLS is used in producing large scale three dimensional prototypes. This study suggests an in-line static mixer with dimensions reduced to a miniature scale. Sintering conditions can be varied to change mechanical properties of the sintered material. However, functional limitations for SLS units depend fundamentally on the laser beam width and layer thickness (step size).

2. Experimental Procedure

2.1 Computer Design of a Prototype

The areas involved in the prototype design were divided into CAD modeling, CAD files conversion, and model evaluation. The CAD model of an inline static mixer was developed in AutoCAD 2004®, taking reference specifications and designs from commercially available devices. To manufacture a prototype by SLS, the design files needed to be correctly formatted and evaluated. The models were created as solids and saved as CAD files (usually extension .dwg). The SLS files, however, are files of extension .stl, and therefore the CAD files need to be converted in order to be compatible with the software of the SLS unit. AutoCAD® allowed us to convert any file into .stl files as long as its contents were solids.

After the file conversion, the models were submitted to a pre-analysis and evaluation process performed by the software of the SLS unit. This evaluation stage was necessary because, once the process of building a prototype was in progress, design errors and adverse features could not be modified.

2.2 Material Analysis

Five samples were sintered using laser power settings of 4.5, 5.0, 5.5, 6.0, and 7.0 Watts respectively using a SinterStation 2000®. Each sintered sample was then subdivided into several specimens for further testing. Optical microscopy and Scanning Electron Microscopy (SEM) were used to assess surface roughness, porosity, sintering efficiency, and other unique microstructural characteristics of virgin powder and sintered specimens.

2.3 Material Properties Enhancement

The availability of many specimens made possible an extensive study of surface roughness enhancement of sintered samples at different intensities. Coatings of polyurethane and epoxy were then applied to the sintered sample specimens. Finally, SEM was used to identify which combinations of coating process and sintering conditions produced surfaces that were smooth and impermeable to liquids.

2.4 Hardness Testing

In order to examine the effect of varying the laser power settings, hardness testing was performed on EOS™ PA sintered samples at different intensities before and after the applied coatings. Hardness testing was performed using the Rockwell P scale which uses a 6.350 mm (1/4 in) ball indenter and a total test force of 150 kg to test very soft materials.[3] Micrographs of the respective indentations were compared to derive further correlations. A separate hardness testing was performed on a 16.51 cm long prototype specimen generally used for tensile testing (dog-bone sample). This sample was tested for hardness along the longitudinal axis with a spacing of 1 cm in between indentations.

3. Results and Discussion

3.1 SEM Results and Particle Size Analysis

Optical microscopy of powder EOS™ PA determined the particle size distribution to have an average of 60 μm. SEM studies performed on the EOS™ PA powder showed that the powder particles were generally uniform spheres or ellipsoidal. However, many of the particles displayed an opening in the middle cross-section with smaller particles visible within the crack-like feature (Figure 1). These smaller particles ranged from 2 to 7 μm and formed part of the larger particulate. The micrograph in Figure 1 revealed that our material is in fact formed by agglomerates of smaller particles (black arrows) and not single particles. Consequently, the remaining powder in sintered parts is due not only to limitations of the process, but also to incomplete sintering in the starting powder.

The phenomenon of partially sintered particles on the surface morphology of a sintered sample is illustrated in Figure 2. This problem results from the next-layer powder coming into contact with the sin-

tered layers before the material crystallization fully takes place in the consolidated matrix of the part under construction. The background of the micrograph (blue arrow) shows a matrix that indicates fully sintered EOS™ PA powder. This micrograph illustrates the presence of agglomerates (black arrows) with a crack-like feature even within the sintered matrix.

3.2 Surface Morphology of Samples

Stereomicroscopy analysis showed that the laser power settings have a significant effect on the surface morphology of sintered samples. The surface morphologies observed presented a uniform trend of having parallel lines of partially sintered material on the surface of the sample. These parallel lines run along the laser scan and sintering direction. It is very likely that non-sintered particles of material adhere to the surface of laser tracks after a scan of material has just been sintered. The variable widths between these parallel tracks suggested that the speed of the sintering laser beam was not uniform in the SLS system used. However, sintering efficiency was found to increase as the sintering laser power increased, and it was determined that a laser power of 7.0 W was optimal for building the prototypes.

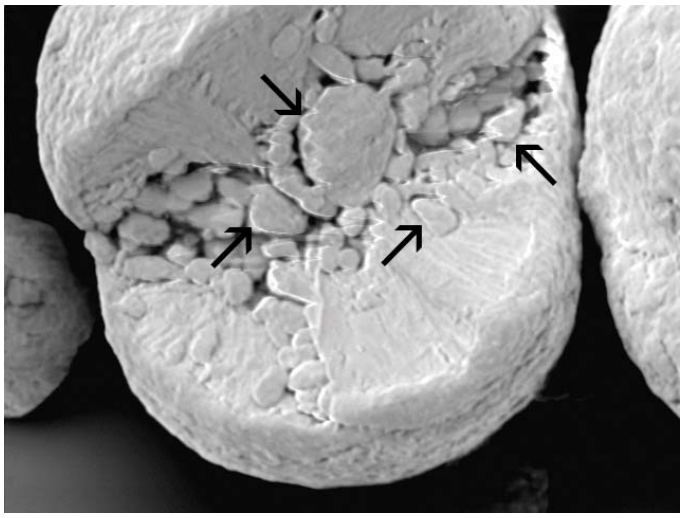

Figure 1. Scanning electron micrograph of powder EOS™ PA

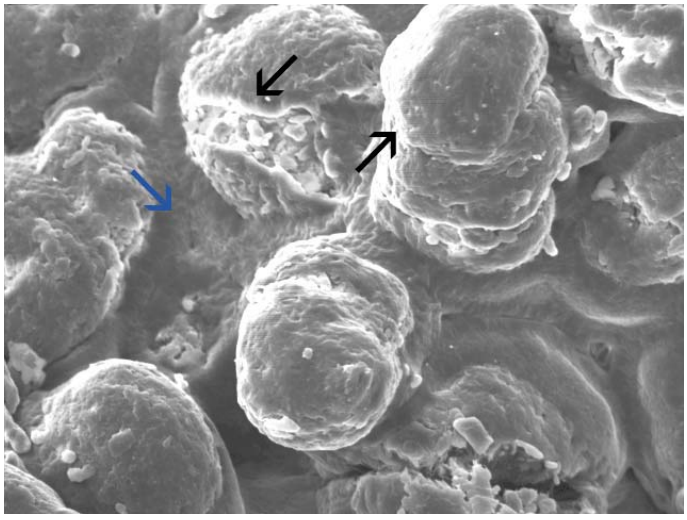

Figure 2. SEM micrograph of sintered EOS™ PA

3.3 Enhancement of Surface Morphology

The use of a polyurethane resin was found to be more suitable for enhancing the surface roughness of sintered EOS™ PA because of its low viscosity. This property allows an easy and practical application for faster results. Figure 3 shows SEM micrographs where coatings with epoxy resin present shattered glassy properties (Figures 3a and 3c). These features were not present when polyurethane resin was used. Polyurethane resulted in a smoother surface on samples sintered at higher power settings (Figure 3d).

3.4 Rockwell Hardness

Deformations from a stress are time-dependent for polymers because of the time it takes for their

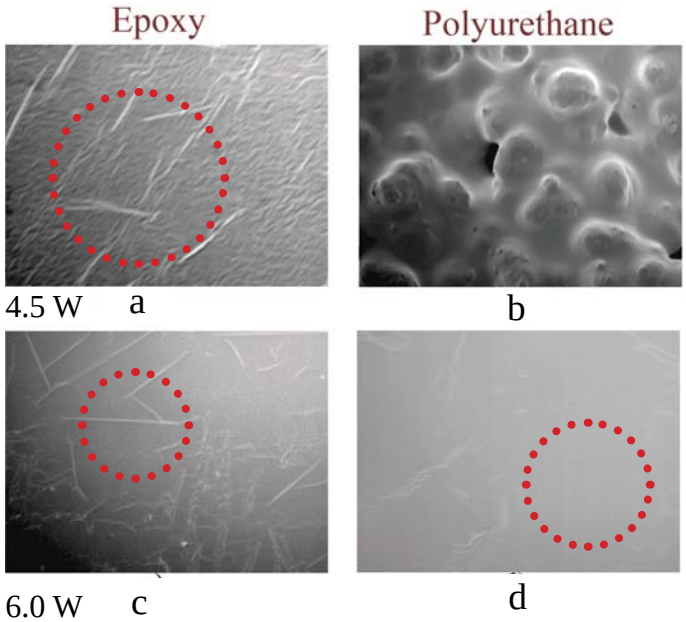

Figure 3. SEM micrographs of coated specimens sintered at different power settings

polymeric chains to unfold. The material's resistance to localized plastic deformation is therefore a time-dependent variable difficult to measure with precision. Due to this time-dependent response of the amorphous polymer used, the values found for hardness are considered to be only qualitative figures that show the trend that was found in the hardness behavior of the material. Therefore, the units for the hardness were determined to be arbitrary (au*) even though, as stated before, the P scale was used. Figure 4 illustrates the increasing values of hardness with increasing sintering-laser power. Coatings with polyurethane and epoxy increased hardness values. The coating with epoxy resin presented higher hardness values compared to polyurethane. Polyurethane resin was chosen over epoxy due to reasons previously stated.

Stereomicroscopy analysis demonstrated that indentation diameters on uncoated samples decreased as the laser sintering intensity increased. The indentation diameters were approximately 2.87, 2.78, 2.71, and 2.55 mm for samples sintered at intensities of 4.5, 5.0, 6.0, and 7.0 W respectively.

The beam speed was found to be non-uniform, and scan space conditions, as stated before (Section 3.2), also affected the mechanical properties of the sintered material. Figure 5 shows that hardness values increased along the longitudinal axis from the center of the measured sample (dog-bone); the results of hardness to the left are almost a mirror image of the results for hardness values to the right. An explanation is that the heat of the build area including the sintered prototypes dissipates through the walls and the bottom of the SLS bed part. The resulting phenomenon is the presence of three-dimensional isotherms that induce differentials in material properties along the sintered segments (parts).[4] From this theory, it can be established that the shrinkage of a sintered part depends on temperature and time.

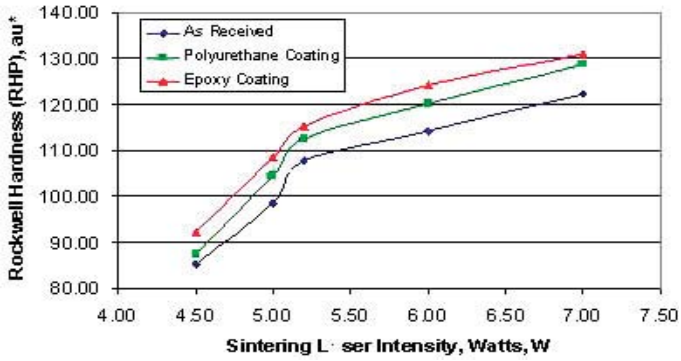

Figure 4. Rockwell hardness values along the axis of a sintered sample

3.5 Stereomicroscopy Results

It was determined that the SLS system used was about 90% accurate in reproducing CAD models with their correct dimensions. This means that the SLS process presents a manufacturing technique capable of supporting designs with critical tolerances. Higher accuracy percentages can be achieved by having a better control and understanding of the variables that play a role in the SLS process. The final parts obtained were not functional devices, but they were demonstrational prototypes that proved the concept of the feasibility of manufacturing small size fluidic

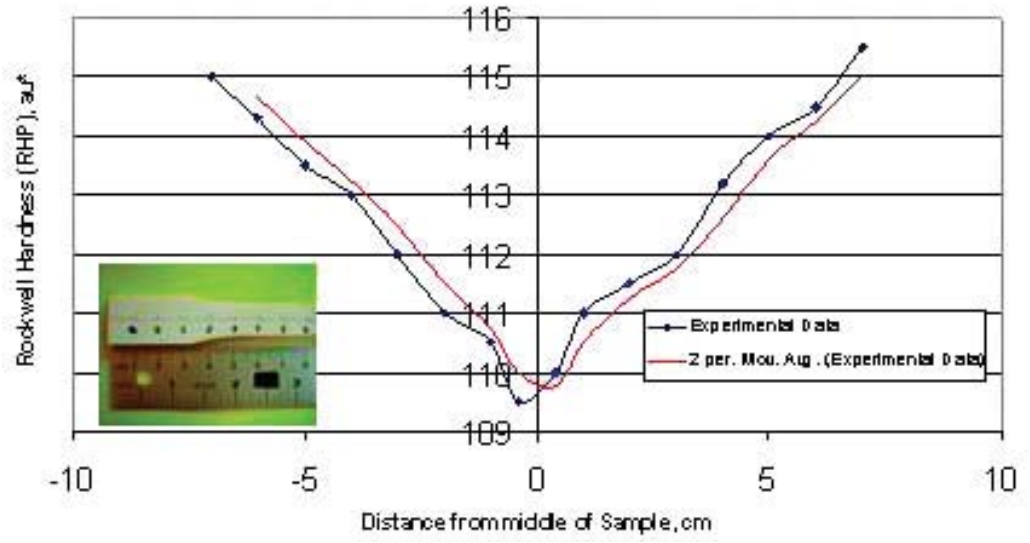

Figure 5. Rockwell hardness values along the axis of a sintered sample.

Figure 6. Small size in-line static mixer prototypes manufactured by SLS

devices by FFM. Figure 6 presents the manufactured in-line static mixers which are considered to be miniature size compared to the commercially available scales (~1-5m).

4. Conclusions

The performed research showed that it is feasible and practical to make prototypes of small size fluidic devices utilizing SLS. Once a CAD model of the fluidic device is drafted and converted to .stl format, an SLS unit can fabricate a three-dimensional prototype of the fluidic device. To make any prototype a functional device the optimal settings need to be determined because several factors affect performance and results. The effect of sintering laser beam speed, scanning space, and bed part temperature is worth noting in order to ensure the production of parts with uniform mechanical properties.

Raising the power of the sintering laser increased the efficiency of sintering nylon particles and reduced agglomerate nucleation sites. Rockwell P hardness tests also confirmed that raising the laser intensity increased strength. SEM and stereomicroscopy analyses confirmed that porosity and surface roughness were reduced when higher laser power settings were used during sintering. The coated prototypes of the miniature in-line static mixer were not tested for functionality. These prototypes were used for demonstrational purposes only. Finally, barriers such as the limited number of readily available materials for SLS still need to be overcome.

Acknowledgements

This paper is based on the results presented during the 2003-2004 academic year by a senior design team (Folgar, Taloma, and Pursoo) to the Department of Materials Science and Engineering at Virginia Tech in fulfillment of graduation requirements. Acknowledgements for their valuable support are given to the team members, Dr. Carlos Suchicital (MSE), Kathleen Rohr (MSE), and Dr. Kevin Creehan (ISE).

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