Stereometric Design for Desk - Top SFF Fabrication

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Abstract

Solid Freeform Fabrication (SFF) technologies refer to the fabrication of physical parts directly from computer based solid models described by STL (Stereo Lithography) or VRML (Virtual Reality Modeling Language) files generated by Computer-Aided Design (CAD) systems. Most of the SFF processes produce parts by building them layer by layer using a row by row pattern, though it is possible to build the part using other patterns. The SFF technology represents a challenge to designers who, in addition to making decisions concerning optimum shape and functionality of the entire part, have to take under consideration several other manufacturing factors. These factors cover a wide range of technical issues such as Computer-Aided Design model generation, part description and model slicing files, laser path files, precision of part design, rendering patterns, manufacturing tolerances, thermal expansion and residual stress phenomena.

This paper investigates the effect of rendering patterns on the integrity, material characteristics and mechanical properties of the parts prepared by a desk-top SFF device using diode lasers. Fe - Bronze (Cu - Sn) premixed metal powders were used as the starting material. The particle size was about 100 μm to 200 μm. Density, tensile strength and microstructure of the parts prepared using different rendering patterns were characterized. The results were analyzed to seek optimal rendering patterns. It was noticed that the samples were strong along the laser scanning direction, while they were weak perpendicular to the scanning direction. These results suggest that the laser scanning patterns should be designed to minimize the warping and maximize the strength of the part in the direction depending on the part's function.

1. Introduction

Solid Freeform Fabrication (SFF) is a Rapid Prototyping (RP) technology that makes it possible to build a part from metal or ceramic powders instead of cutting it out of blocks larger than the part dimension. The SFF process consists of two steps [1,2]:

a) design parts using CAD methods to form a STL, VRML, or other file that, in turn, will be sliced and inputed into algorithms for generation of the paths for fabricating the SFF product; and
b) manufacture the physical component by layering 2D sections with a small third dimension measurement.

A wide variety of RP technologies have been proposed during the last decade; these technologies can be used for the purpose of rendering 3D objects out of resin, plastic, ceramic, or metal powder[3]; but only a few were successfully applied to building structurally strong parts. One of them is SFF technology which allows for building objects from powders by thermal fabrication. The heat source in the SFF process is normally a laser impulse in the infrared region of the electromagnetic spectrum. This technology presents a real opportunity for designers. They would have a chance to design and produce a part that would fit directly to the design or reconstructed system.

In spite of the fact that Selective Laser Sintering (SLS), Selected Area Laser Deposition (SALD) and Selected Area Laser Deposition Viper Infiltration (SALDVI) [1,5,9,10] are
successfully used to prepare some parts in laboratories, there is an entire group of questions awaiting answers before a widespread industrial application of SFF can take place. These questions address the use of CAD systems, representation of the part model communication between CAD systems and the sintering setup, and effectiveness of the sintering process. Some of these questions can be readily solved, as for example the statement that the dimensional tolerance of a part cannot be smaller than the diameter of the laser beam, but other questions require further studies. The aspects that require studies are: orientation of the part, optimal shapes of the part for SFF processes, configuration of the part, and the relation between the part mechanical properties and the rendering patterns. In this paper, the effect of rending patterns on the integrity, microstructure and mechanical properties of the part is investigated.

2. Desk-Top SFF System and Design and Rendering of Samples

The apparatus used in this research is a desktop SFF apparatus built in our laboratory. The apparatus is equipped with four kinds of software: the CAD software, slicing software, the laser path design software and the laser path control software. The primary functions and components of the apparatus are shown in Fig. 1. The apparatus includes a diode laser power system [4,5], powder feeding system, oxidation prevention system, and laser scan control system.

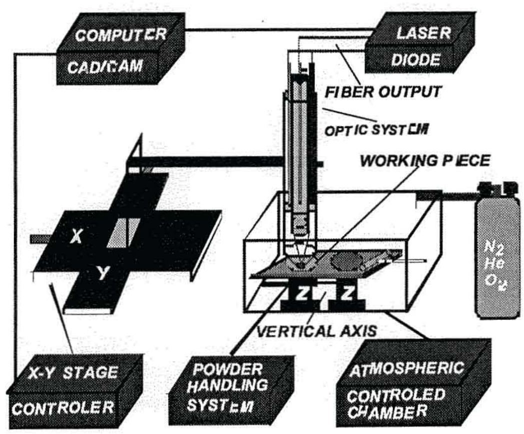

Fig. 1. Schematic diagram of the desk-top SFF system.

The solid models were designed using Cadkey software [6]. The Cadkey data were exported into STL file format [7,8]. The STL data are then converted into a Direct Motion Control (DMC) machine language tool path description in the desired pattern [11]. The application for the conversion was created especially for the project. The DMC format was compiled using Galil software [11]. The Galil software utility downloads the compiled data to a controller card attached to the computer. The controller card controls the separate X and Y servo step motors through a closed loop data feedback.

A total of six different scanning patterns, as shown in Fig. 2, were generated. The first scanning pattern was a horizontal scan, the second was a vertical scan, the third was a horizontal scan with skips, the fourth was a vertical scan with skips, the fifth was a random grid scan, and the sixth was a mix of horizontal and vertical scans. Every sample had three layers. This was done by sintering a powder layer with a diode laser, followed by laying down a new powder layer on top of the sintered one, layer-by-layer, to form a 3-D structure.

The material was a composition of pre-mixed powder (Fe $_{34\text{-}36}$, Cu $_{58\text{-}60}$, Sn$_{6\text{-}7}$) with particle sizes of 100 - 200 μm. The thickness of each powder layer was either 1 mm or 0.5 mm. However, it was found that the 1 mm layers did not bond well to each other, suggesting that sintering was not sufficient with 1 mm layers. As such, most of the samples fabricated had a powder layer thickness of 0.5 mm. Further, the results presented in this paper were obtained from samples made with layers of 0.5 mm thick, unless otherwise stated.

The laser spot diameter was 0.8 mm. The scan speed was 0.8 mm/sec with path axes speed 0.5 mm apart apart 0.5 mm (0.3 mm overlay). The spot temperature was in the range of 800 - 900 degrees C and the powder bed temperature was 80 - 200 degrees C. The experiment was done in flowing argon gas with a diode laser of 810 nm and a laser power of 15 watts.

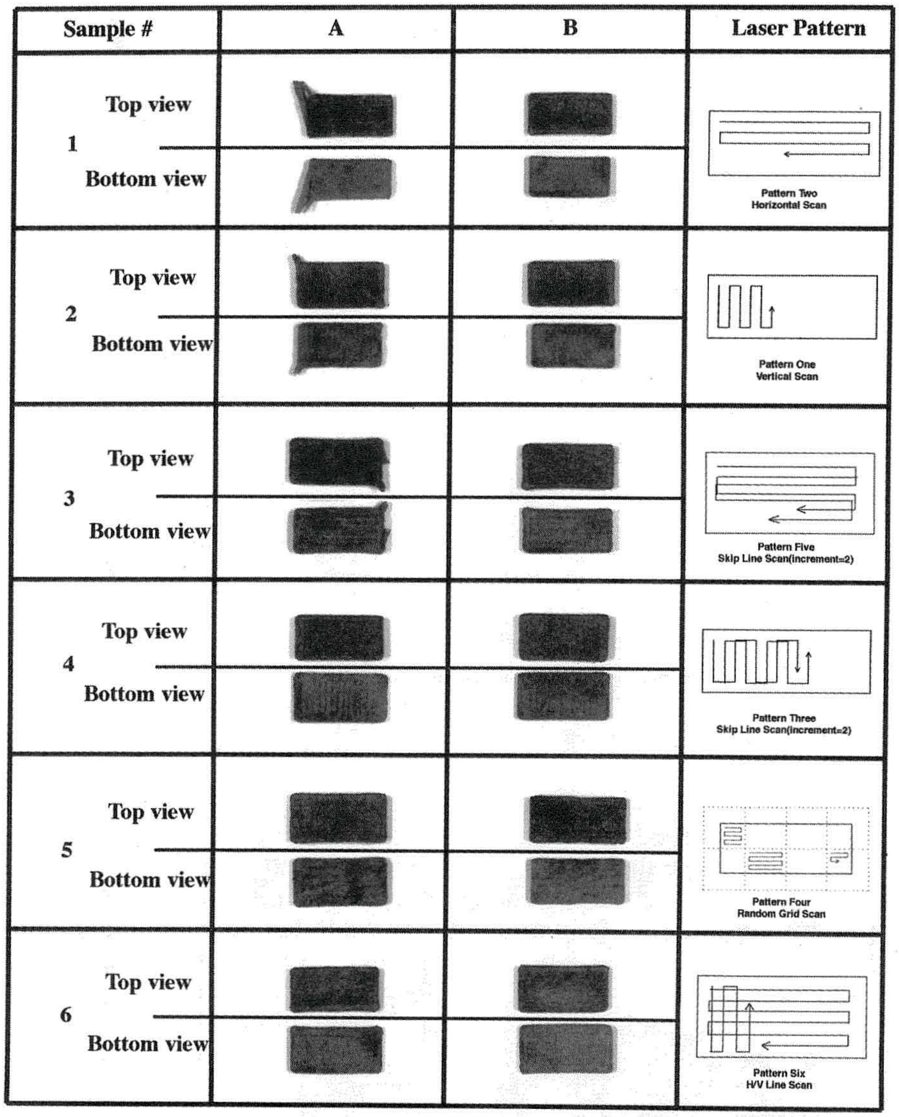

Fig. 2. The set of six test samples with different scanning patterns.

3. Sintered Parts and Their Properties

The physical images of six test samples are shown in Figure 2. Note that samples #1, #2, and #3 had small "tails". This was due to the fact that in those samples the origin of rendering was set up beyond the boundaries of the sample. This was slightly corrected in the sample #2 and an even bigger correction was done when generating sample #3. The tail was clipped completely when samples #4, #5 and #6 were generated. To clip the tail completely the origin of the laser path pattern was moved into the middle of those samples.

The surface roughness, density, tensile strength and microstructure of all the samples were characterized. The results are summarized in Table 1 (density and tensile strength), Fig. 3 (the load vs. displacement curve), Fig. 4 (surface roughness), and Fig. 5 (microstructure). It was found that the densities of samples made through six different scanning patterns were similar and all of them were about 40% of the theoretical (Table 1). The low density of the sintered material was apparently due to the low density of loose powder used. A powder slurry has been considered to improve density in the future, . The microstructure examined, as shown in Fig. 5, was consistent with the density measurement, i.e., there were many pores in the sample. Samples #1, 2,4, 5 and 6 (not shown in Fig. 5) also had microstructure similar to #3 . The tensile test indicated that the strength of the samples was stronger along the laser scanning direction than perpendicular to the scanning direction. However, the strength obtained was far below the tensile strength of Fe or Cu metals. This was not a surprise since there was a substantial amount of pores in the samples. It was also noted that different scanning patterns (e.g., samples #1, 3, 5 and 6) did not seem to offer substantially different strengths. However, more work is needed to further elucidate this.

Sample #	Relative Density (%)	Tensile Strenght (MPa)
1	36.2	7.6
2	36.7	4.4
3	40.8	5.9
4	37.5	3.5
5	36.8	6.9
6	37.3	7.1

Table 1. Density and tensile strength of samples with different scanning patterns

The tensile test results, recording load vs. displacement, are shown in Fig. 3. The surface roughness of sample # 3 is shown in Fig. 4. One can notice that the width of the laser path scans was about 0.5 mm with an overlap of about 0.3 mm. This agrees with the actual scan settings.

4. Warping and Distortion During Sintering

The sintering process resulted in warping and distortion of layers. This was expected. The degree of warping and distortion depended on the laser scanning pattern. With all patterns the warping was severe enough that part of each layer protruded above its intended plane a distance greater than the layer thickness. During the sintering process, powder added for a subsequent layer could not be plowed and smoothed to the proper height because of the protrusion. Instead the powder was smoothed using the peaks of the underlying layer as a guide. The depth of the powder for subsequent layers became variable. As a result, the powder thickness away from the peak could exceed the desired thickness, while near the peaks the thickness tapers to zero. With a given pattern of peaks the depth of subsequent layers also varies depending on the direction the powder is plowed in. When the powder was plowed so that the peaks occur in parallel then the powder would fill the depression between the peaks. When the powder was plowed so that the peaks occurred in series, there would be less powder overall and some areas wouldn't have any powder at all. The protrusion of the peaks also made it difficult to plow the powder without shifting the underlying pieces of sintering material. Samples which were accidentally shifted had to be discarded.

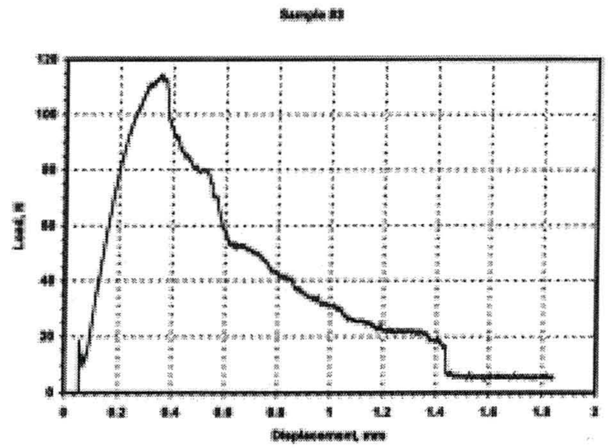

Fig. 3. The tensile test results of sample #3.

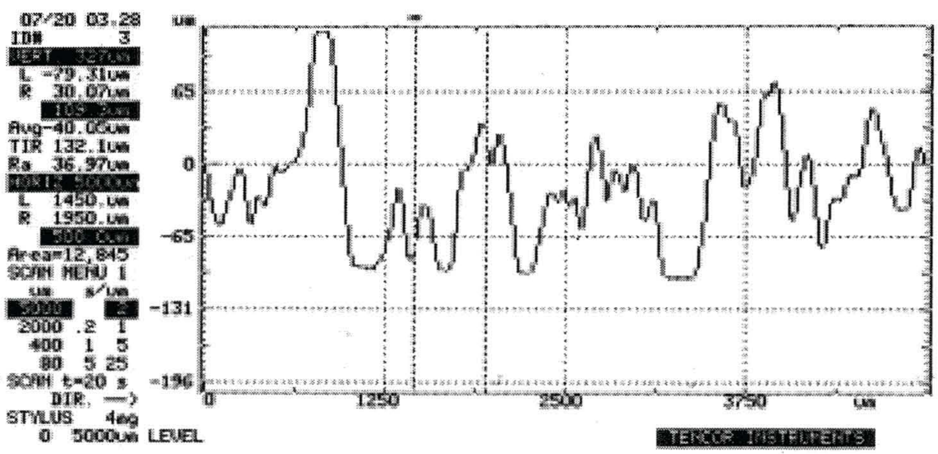

Fig. 4. The surface roughness of sample #3.

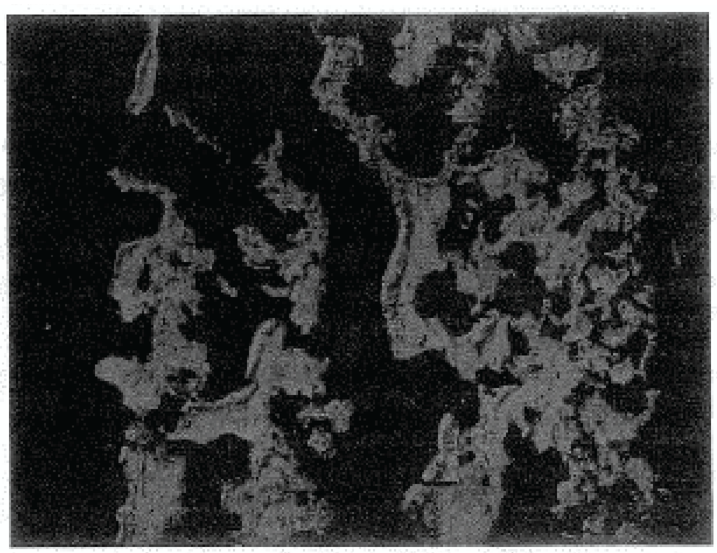

Fig. 5. The optical image of the cross section of sample #3. The bright area shows metals, while the dark area is porosity.

5. Conclusions

This paper concentrated on the laser pattern design to minimize the warping and distortion of layers during rendering and to maximize the density and mechanical properties. Certain laser scanning patterns help to release heat so that warping and distortion can be minimized; but these patterns may not be advantageous from the viewpoint of the density and strength of the material. It was found that the densities of samples made using different scanning patterns were similar. However, the tensile strength of the samples exhibited substantial dependence on the scan direction. In general it was noticed that the samples were strong along the laser scanning direction, and weak perpendicular to the scanning direction. These results suggest that laser scanning patterns should be designed to minimize the warping and maximize the tensile strength of a part in the direction according in which the tensile strength is the critical.

6. Acknowledgments

The desk-top sintering device was developed at the Photonics Research Center, where the described samples were fabricated. The samples were tested in the Institute of Material Sciences Laboratories. The research on design methods was conducted at the following University of Connecticut institutions: Mechanical Engineering CAD&CAM and Expert Systems Laboratory, Photonics Research Center, Institute of Material Science and the departments of Mechanical Engineering and Metallurgy. The authors appreciate all the support provided by the leadership of these institutions and help of colleagues, especially Prof. Harris Marcus, Jim Crocker and the other members of the IMS SFF group.

7. References

[1] Manzur T., Roychoudhure C.S., and Marcus, H.L., 1996, “SFF Using Diode Lasers”, *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, Austin, TX, August 1996; SFF Symposium Proceedings, pp. 363 - 368.

[2] Wang, Y., Dong, J. And Marcus, H.L., 1997, “The Use of VRML to Integrate Design and Solid Freeform Fabrication”, *Proceedings of the Solid Freeform Fabrication Symposium*, University of Texas at Austin, TX, August, 1997, pp. 669 - 676.

[3] Bzymek, Z.M.., Benson, S., Garrett, R.E. and Ramakrishnan, B.T., 1996, "Thermo-Printing and Laser Sintering Slicing Simulation for Rapid Prototyping of Engine Parts", 29th ISATA International Symposium on Automotive Technology and Automation, June 6 - 9, 1996, Florence, Italy; *29th ISATA Conference Proceedings: "Simulation, Diagnosis and Virtual Reality Applications in the Automotive Industry"*, pp. 291-298.

[4] Chen, W., Roychoudhuri C.S., and Bana S.C., “Design Approaches for Diode Laser Material Processing System”, *Optical Engineering*, Vol. 33, pp. 3662-3669.

[5] Manzur T., Roychoudhure C.S., Dua P., Hossain F. and Marcus H.L., 1997, “Net shape Functional Parts Diode Laser”, Solid Freeform Fabrication Symposium 1997, University of Texas at Austin, Austin, TX, August 11 - 13, 1997; *SFF Symposium Proceedings*, pp. 99 - 114.

[6] Cadkey 97, 1997, *www.cadkey.com.*, Baystate Technologies Publications, Baystate Technologies, 33 Boston Post Road West , Marlborough, MA 01752, USA.

[7] Yanshuo Wang, “Computer Interfacing and Virtual Prototyping for SFF”, *MS Thesis*, University of Connecticut, 1997, J. Dong, H. Marcus, Z.M. Bzymek - advisors.

[8] Dong, J., 1996, “Issues in Computer Modeling and Interfaces to Solid Freeform Fabrication”, 1996, *Proceedings of the ASME Winter Congress and Exposition*, Atlanta, GA, pp. 34 - 43.

[9] L. Sun, K.J. Jakubenas, J.E. Crocker, S. Harrison, L. Shaw and H.L. Marcus, “Thermocouples in Macro-Components Fabricated Using SALD and SALDVI Techniques: Part II - Evaluation of Processing Parameters”, *Materials and Manufacturing Processes*, in press (1998).

[10] J.E. Crocker, K.J. Jakubenas, S. Harrison, L. Shaw and H. Marcus,1997, "SALDVI Optimization for the Tetramethylsilano - Silicon Carbide Systems", *Proceedings of the 8th Annual Solid Freeform Fabrication Symposium*, The University of Texas at Austin, pp. 489-496.

[11] *DMC - 1000 Technical Reference Guide*, Version 1.3, rev. 1.3, 1994, Galil Motion Control, Inc., 575 Mande Court, Sannyvale, CA 94086 - 2803.