International Journal of Applied Science and Engineering
2012. 10, 1: 59-68

Investigation of Dimensional Accuracy/Mechanical Properties of Part Produced by Selective Laser Sintering

Sharanjit Singh*, Anish Sachdeva, and Vishal S Sharma

Department of Industrial and Production Engineering, Dr. B R Ambedkar National Institute of Technology, Jalandhar, India

Abstract: Selective laser sintering (SLS) process has the potential to become one of the most useful additive manufacturing techniques in coming few years, because it has potential to easily produced complex shapes. Use of this process becomes more extensive, with the main advantages being a wide range of build materials available. So SLS can accommodate multiple applications throughout the manufacture process. It comes early with three main applications: conceptual models, functional prototypes, and pattern masters. Since then they have been added with an extra module, which incorporates rapid tooling. Only disadvantage of SLS process that it is both time consuming and expensive when a new material comes into use. In this paper we will investigate the effect of part placement (X and Y direction) in the build on the dimensional accuracy and mechanical properties of part produced by this SLS process.

Keywords: Rapid manufacturing; Selective laser sintering; dimensional accuracy; mechanical properties

1. Introduction

In SLS process the parts can be made out of common engineering thermo-plastics such as polyamides, ABS, polycarbonate, nylons to metal parts such as titanium, stainless steel and tool steel [1]. RP has grown as integral part of the new product development process, since the delivery of the first commercial machine. With the help of rapid manufacturing the production time and production cost of product has been reduced. But there is one major drawback of this process regarding the part accuracy. This is main worry of industries such as aerospace and bio-medical which would like to use this technology for producing directly usable products. The capability to produce a part in hours without any tooling is a great advantage for many industries. With the stronger plastics and even metallic materials used in some of the RP processes, parts can be produced that will withstand reasonable amount of stress and higher temperature ranges. In order to improve the accuracy of the part, the shrinkage behavior of parts during manufacture needs to be better understood.

Selective laser sintering (SLS) is a rapid manufacturing process by which we can directly produce the parts from CAD model without part specific tooling. In this process metallic and nonmetallic parts can be produced layer by layer as shown in Figure 1. SLS uses fine powder which is spread uniformly by a roller on the machine bed and scanned selectively by a laser of power

* Corresponding author; e-mail: malhi.sharanjit@gmail.com

Received 11 April 2011
Revised 2 October 2011
Accepted 12 December 2011

25–100W such that the surface tension of the grains is overcome and they are sintered together. First powder is pre-heated to temperature slightly below the sintering temperature of the material by infra red heaters to minimize thermal distortion and to facilitate fusion to the previous layer. Laser then scans the cross-sectional area identified for the current slice, thus sintering of the powder takes place. After this again a fresh layer of powder is deposited across the part bed, and the process is repeated until the final part has been completed. During this process the previous layers of un-sintered powder act as a support for any overhanging features. Once the build is complete, the part, encased in un-sintered powder, is left to cool to approximately 40 ◦C, at which point the powder is brushed away, revealing the final part.

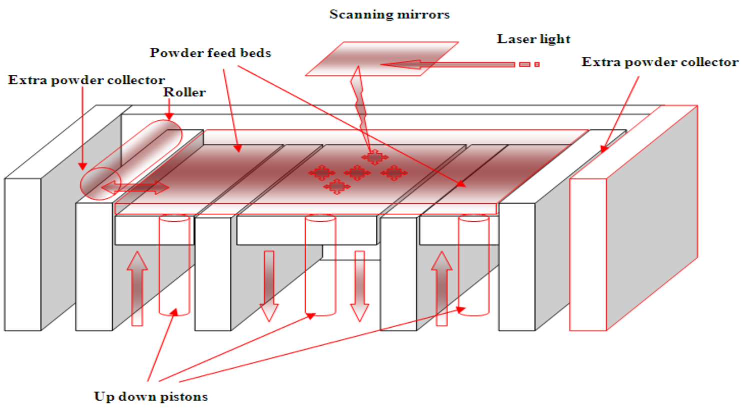


Figure 1. Block diagram of Selective laser Sintering (SLS) process [2]

2. Literature review

As explained earlier SLS is one of the rapid manufacturing processes from which we can produce durable and functional parts from a wide range of prototype materials. The parts are wear resistant, durable and chemical resistant [3]. These parts can be made to bend, snap or assemble together and form flexible hinges [4]. Still, parts produced by SLS are unfortunate in terms of accuracy due to the various errors accumulating from data preparation stage to finishing stage. One of the main reasons of size and shape variations of the part is shrinkage during processing. In the below paragraphs we explain some of the earlier work carried out by researchers to study shrinkage in SLS process.

First in 1996 Rock and Misiolek [5] provided a general idea of powder- based rapid prototyping processes with particular emphasis on the freeform powder molding process. The causes of distortion were investigated and traditional distortion controlling approaches were reviewed. An experimental technique was formulated for characterizing process-induced distortion arising from non-uniform component shrinkage, and the experimental outcomes highlighted the often overlooked role of component geometry on the distortion. Their research led to fairly enhanced computational system capability of automated compensation for process-induced distortions.

Childs et al. [6] reported on the thermal and powder densification modeling of the SLS of amorphous polycarbonate. The investigation had been done with three strategies i.e. analytical, adaptive finite mesh difference, and fixed finite mesh element. An assessment between the three strategies and the experimental outcomes was used to reliably estimate their ability to forecast the behavior of the physical process. The investigation showed that the densification and linear accuracy due to sintering were generally sensitive to changes in the activation energy and heat capacity of the polymer. As less important factors of the linear accuracy, the powder bed density and the powder layer thickness were included. The authors furthermore showed that simulations of manufacturing hollow cylinders and T-shapes feature distortions because of the excessive depth of sintering at the downward-facing surfaces in the powder bed.

Wang et al. [7] in 2007 made a detailed study by using neural networks for the effect of process parameters on shrinkage in SLS process. They found that percentage shrinkage increases with increase in the scanning speed and hatch spacing, but shrinkage generally decreases with increasing layer thickness, laser power, delay time and part bed temperature. Ragunath and Pandey [8] also studied the effect of process parameters on the process and material shrinkage. They found that scan length influences shrinkage in the X direction. They also found that scaling factors can have a linear relationship with scan length and derived empirical relations for percentage shrinkage in terms of scan length by using Taguchi method. Further, they used scaling factors based on the maximum dimensions not on the individual scan lengths while compensating using the model developed by them.

Zhang and Faghri [9] investigated the different melting points of a mixture of two powders under the regular melting process in a physical model. The temperature distributions in liquid and solid phases during the SLS process were studied. Porosities of powder generated shrinkage when they were changed into the liquid phases of the sintering process and the effects were projected as a method through which the shrinkage of the SLS process can be simulated.

Hopkinson and Sercombe [10] studied the effect of part height, part position and build direction on the shrinkage during indirect SLS by using aluminum powder. They found that errors diminish with increase in nominal dimensions in infiltrated state than in a green state for all build condition. They further found that error in Z direction is more pronounced than in-plane errors due to phenomenon called "Z-growth" whereby the heat from the laser penetrates beyond the down facing surface to bond unwanted particles. They characterized tolerances feasible on different build orientations and initiate that a tolerance of ±0.1 mm is achievable for a 40 mm part in the XY direction and ±0.3 mm in Z direction. Zhu et al. [11] investigated the shrinkage behavior in metal powders. They quantified two types of shrinkages namely thermal shrinkage and sintering shrinkage. They found that in-plane shrinkage (X and Y shrinkage) is very fewer as compared to the shrinkage in the build direction. They further found that the sintering shrinkage is mainly caused by densification and is a kind of elastic compressive reduction. They recommended that thermal shrinkage due to cyclic heating can be lowered by controlling process parameters. They investigated that, the thermal shrinkage increases with increase in laser power and shrinkage decreases with increase in scan speed and scan spacing. Ning et al. [12] measured the effect of geometry on the shrinkage of metallic parts. They provided the speed compensation technique based on the scan length. In their method, when building a part, the laser scan speed is adjusted dynamically according to the scan length which varies with geometric shape of the part. The different scan speeds for the scan lengths are selected based on the shrinkage values at different speeds.

Ning et al. [13] made number of experiments for direct metal laser sintering (DMLS) process to discover the effect of hatch length on the material anisotropy, heterogeneity and part strength. They concluded that short hatch lines cause serious shrinkage and the part becomes less homogeneous. They formulate an algorithm to locate optimal hatch direction for a typical layer by taking into account the shrinkage as a function of hatch length. Manetsberger et al. [14] investigated the effect of temperature, time and pressure on the shrinkage of polymer parts. They used a thermal simulation as a basis for shrinkage compensation in SLS process. They articulated shrinkage values as a function of temperature and also showed a linear dependency to the pressure applied. Further Jacobs [15] studied the effects of shrinkage variation on the accuracy of rapid tooling inserts. This work mainly concentrated on random shrinkage and initiate that standard deviation of random shrinkage is directly proportional to the mean process shrinkage. He also originate that no uniformity in shrinkage is mainly attributed to geometry of the part. He summarized that key to accuracy and repeatability of such techniques is the decline of mean process shrinkage to a smallest possible level. Wang [16] considered the issues in calibration of shrinkage and beam offset for the SLS process. Author developed expressions for shrinkage and beam offset in terms of the nominal diameter and error after sintering and the effect of part weight on the percentage shrinkage also taken into account.

3. General factors effecting accuracy

It is very difficult for us to achieve the desired accuracy in the parts which are produced different rapid manufacturing processes. The major reason regarding accuracy is as it is a function of many different factors, some of which can be interdependent. The factors that most influence RP accuracy are basic STL files and material used.

In this SLS machines the CAD model is employed in the standard STL input file format. It approximates the surface of the three dimensional CAD model by triangles. Facets are hard to avoid on curved surfaces and can sometimes appear on the final model. The accuracy of STL files can be controlled at the time of their generation by modifying the chord height and the angle control factor. Unluckily, if triangles small enough to generate, very soft surfaces are generated, large data files will work otherwise [3]. There are varieties of metallic and polymer based materials which can be processed by SLS. All have different properties and characteristics that can have an effect on part accuracy. The main cause of part inaccuracy is the shrinkage during sintering which does not always take place in a uniform manner. The shrinkage of a new layer can be constrained by the existing part substrate or by support powder trapped within enclosed areas. In addition, areas at high temperatures have a tendency to shrink more than those at lower temperatures and part geometries such as thick walls or sections can increase the shrinkage. To compensate for shrinkage, a scaling factor is applied in each direction to the STL file. On the other hand, scaling a three-dimensional faceted file uniformly is not a simple task and the resulting geometry can be slightly distorted compared with the nominal geometry, depending on the different scaling technique used.

4. Experimentation

In the SLS process there are number of process parameters that are strongly controlled by the operator. The process parameters have been decided by the knowledge, literature review and experience of the machine operator. The various process parameters include layer thickness, laser power, hatch spacing, scanning speed, part bed temperature and scanning mode as shown in Table 1.

4.1. Selection of process parameters

The range of 25-100W laser power available with CO2 laser in the machine used for experimentation. Generally 62% of the maximum power is used in the experiment because curling is examined at higher laser powers.

Scan speed as 2.54 m/s is taken to lower the build time. The laser spot size and energy density used in the experiments are also according to requirements. The process parameters used for contour exposure are lower laser power and scan speed compared to hatching exposure in order to achieve a good surface finish. If the part is not permitted to cool in controlled environment for long time, the part tend to warp due to faster cooling in outside environment. During faster cooling part develops significant stresses causing post-build war page. So the part is allowed to cool inside the platform for 4-5 h.

Table 1. Process parameters set for the experiments

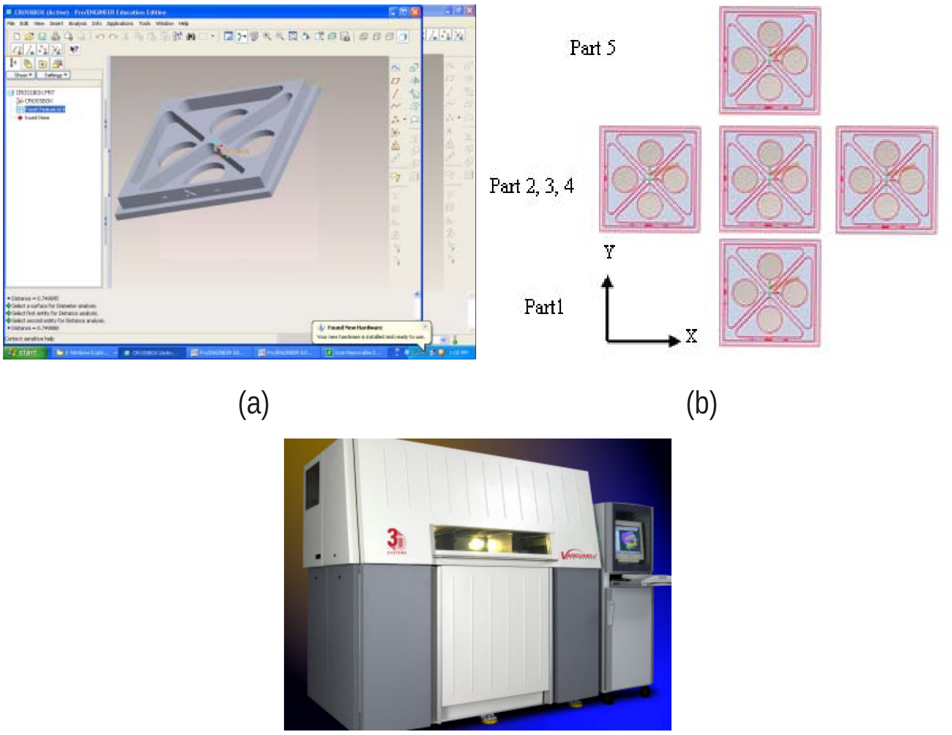
S No.	Parameters	Value
1.	Build chamber temp. (C°)	176
2.	Left Feed set Point(C°)	130
3.	Right Feed set Point(C°)	130
4.	Laser power (W)	29.5
5.	Scan speed (m/s)	2.54
6.	Layer thickness (m)	0.1×10^{-3}
7.	Hatch spacing (m)	0.26×10^{-3}
8.	Scan Count	1

4.2. Details of material

Specimens Figure 2 (a) used in the study are fabricated by using Polyamide Duraform powder having particle size 75 to 100 μm. The material is semi-crystalline in nature. In an SLS process generally we use mixture of fresh powder and previously used but unsintered powder for building parts. After gone through a heating cycle, the previously used powder has properties which are different from virgin powder. The material used was refreshed and the ratio of mixing is 70% used powder and 30% virgin powder. Use of more amounts of fresh powder cause curling in product, so only 30% fresh powder can be used to produce parts [17].

4.3. Layout of SLS test parts

In this SLS set up these five parts are made in process station (Vanguard HS) as shown in Fig 2 (c). The parts are actually situated in the build as shown in the Fig 2 (b). Central part (Part 3) is exactly at the center of the build and the other pasts at the equal distances from the center i.e. the origin of other parts at 35mm away from the center of the build. It was known qualitatively, from sintering performance experience, that there is little delay in sintering of parts placed in the same plane/build. So further tests, i.e. the manufacture of different parts are carried out over the same range of parameters as for the rectangular blocks, to provide samples for the different measurements.



(a) (b)

(c)

Figure 2. (a) CAD model of specimen used to study, (b) Layout of different parts placed in machine bed, (c) SLS setup used for fabrication of parts

5. Measurements

(a) Dimensional accuracy: Dimensional accuracy of SLS specimen's as shown in Fig 3(a) is expressed by error S1, for each value, three measurements are taken and the average value is taken. Dimensional accuracy of the part is represented with the dimensional error S1, which is defined as:

$$S_1=\left[\frac{A_1-A_0}{A_0}\right]\times 100\% \quad (1)$$

where A0 is the design size given by the computer, A1 is the actual size measured by a varnier caliper.

(b) Mechanical properties: Following are the different mechanical properties like tensile strength, elongation at break and density of SLS specimens examined under ambient conditions. The tensile specimens were tested at universal testing machine as shown in Figure 3(b).

(c) Microstructure: Surface photographs have been taken with the metallurgical microscope.

6. Results and Discussion

6.1. Dimensional accuracy of different parts

The dimensional accuracy of the different parts has been measured and the results are shown in Table 2. From the results we find that this polyamide powder expands during sintering. This expansion acutely influences the accurate powder spreading and eventually influences the dimensional accuracy of specimens, with a maximum error of up to 0.192 per cent. The main reason for this expansion is that powder has a high linear expansion ratio. Further the effect of part layout on the accuracy has no obvious difference as the distance in X axis and Y axis increases from the origin, there is little increase in dimensional accuracy error S% as the distance in Y axis progresses.

6.2. Mechanical properties

The mechanical properties of the polyamide SLS specimens are listed in Table 3. From calculated values we find that tensile strength and elongation at break of these SLS specimens are very poor. The main reason is that these parts have a low density and a huge number of cavities inside. Further the effect of layout on mechanical properties on different parts, as we progresses along Y axis there is little decrease in mechanical properties.

Table 2. Dimensional accuracy of SLS Parts

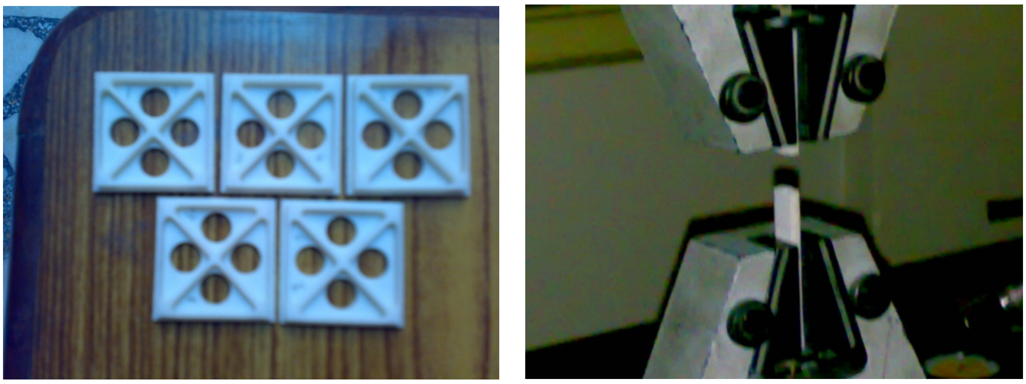
S No.	Measurements		A_0	Dimensional accuracy of different part				
				S_1% of Part 1	S_1% of Part 2	S_1% of Part 3	S_1% of Part 4	S_1% of Part 5
1.	Length of side	X	30	0.25	0.264	0.258	0.254	0.265
		Y	30	0.26	0.263	0.257	0.261	0.264
2.	Width of rib	X	1	0.12	0.18	0.09	0.07	0.19
		Y	1	0.12	0.19	0.06	-0.03	0.19
3.	Thickness	Z	3.75	0.33	0.333	0.333	0.336	0.370
4.	Circle at center	R_1	1.5	0.073	-0.04	0.113	0.133	-0.14
		R_2	1.5	0.086	-0.033	-0.02	0.186	0.03
		R_3	1.5	0.060	-0.006	0.106	0.146	0.12
		R_4	1.5	0.04	-0.04	0.046	0.113	0.04
5.	Thickness of Base	Z	1.25	0.416	0.448	0.464	0.456	0.528
6.	Avg.	S%		0.138	0.156	0.170	0.192	0.185

Table 3. Mechanical properties of SLS parts

S No.	Mechanical Properties	Values of different parts				
		Part 1	Part 2	Part 3	Part 4	Part 5
1.	Tensile strength (MPa)	47.49	47.48	47.48	47.48	47.45
2.	Elongation at break (%)	17.3	17.2	17.2	17.0	17.1
3.	Density (gm/cc)	0.960	0.958	0.558	0.57	0.595

The photographs of different samples are taken on metallurgical microscope as shown in Fig 4. From these we finds that the powder particles are not closely packed, and we can still easily finds the different powder particles. Only adjoining particles join together these results different pores in the parts, which are evident of evolved gases from the sintered part/engulfed air bubble.

These are possible due to the evaluation of gases during the solidification process, and results in decrease of mechanical properties of different parts.



(a) (b)

Figure 3. (a) Photograph of different specimens to measure S%, (b) Photograph of universal testing machine with sample

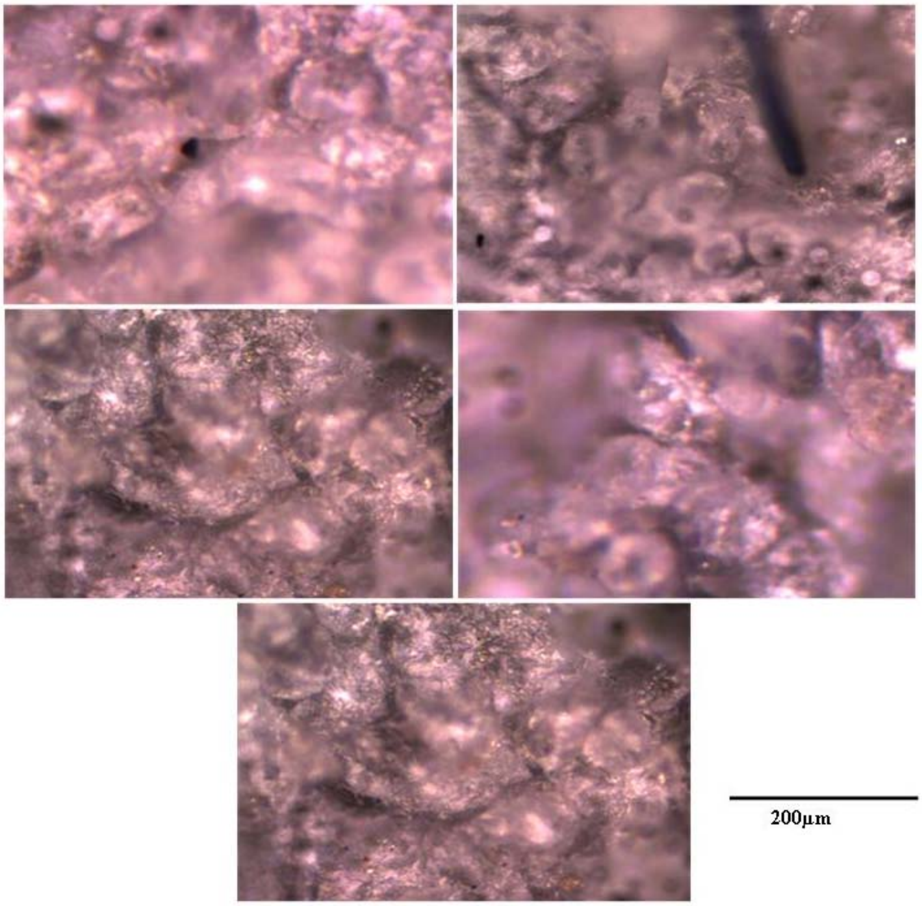


Figure 4. The microstructure of different parts 1, 2, 3, 4 and 5 as shown in layout respectively

7. Conclusion

In the dimensional accuracy of different parts comes maximum error of up to 0.192 per cent. There is little increase in dimensional accuracy error S% of parts as we progress towards Y axis in the build.

In the case of different mechanical properties of parts are deprived due to high porosity, results that parts are weaker in strength. In this case same effect also seen i.e. as we progresses along Y axis there is little decrease in mechanical properties.

There is not too much effect of part placement in the build on the dimensional accuracy as well as different mechanical properties in X direction. But as discussed above it has some influence in Y direction.

Acknowledgements

The manufacturing and experimentation of parts have been done at Rapid Prototyping Center, Center Tool Room Ludhiana, Punjab, INDIA.

References

[1] Chua, C. K., Leong, K. F., and Lim, C. S. 2003. "*Rapid prototyping: principles and applications*". World Scientific, Singapore.

[2] Singh, S., Sharma, V. S., and Sachdeva, A. 2011. Optimization & analysis of shrinkage in selective laser sintered Polyamide parts. *Materials and Manufacturing Processes*, DOI: 10.1080/ 10426914.2011.593247

[3] Cooper, K. G. 2001. "*Rapid prototyping technology: selection and application*". Dekker, New York.

[4] Pham, D. T. and Dimov, S. S. 2006 "*Rapid manufacturing*". Springer-Verlag London.

[5] Rock, S. J. and Misiolek, W. Z. 1996. Distortion control for P/M-based rapid prototyping of advanced material components. *World Congress on Powder Metallurgy & Particulate Materials*, Washington, DC., June 8th to June12th, 1996.

[6] Childs, T. H. C., Berzins, M., Ryder, G.R., and Tontowi, A. 1999. Selective laser sintering of an amorphous polymer-simulation and experiments. *Proc. Instn. Mech. Engrs part B* 213: 333-349.

[7] Wang, R. J., Wang, L., Zhao, L., and Liu, Z., 2007. Influence of process parameters on part shrinkage in SLS, *International Journal of Advanced Manufacturing Technology,* 33: 498–504.

[8] Ragunath, N. and Pandey, P. M. 1999. Improving accuracy through shrinkage modeling by using Taguchi method in selective laser sintering. *International Journal of Advanced Manufacturing Technology,* 47: 985-995.

[9] Zhang, Y., and Faghri, A., 1999. Melting of a subcooled mixed powder bed with constant heat flux heating. *International Journal of Heat & Mass Transfer*, 42: 775-788.

[10] Hopkinson, N. and Sercombe, T. B., 2008. Process repeatability and sources of error in indirect SLS of aluminium. *Rapid Prototyping*, 14:108-113.

[11] Zhu, H. H., Lu, L., and Fuh, J. Y. H. 2006. Study on shrinkage behavior of direct laser sintering metallic powder. *Proc IMechE Pt B: J Eng Manuf* 220: 183-190.

[12] Ning, Y., Wong, Y. Y. S., and Fuh, J. Y. H. 2005. Effect of control of hatch length on material properties in the direct metal laser sintering process. *Proc IMechE Pt B: J Eng Manuf,* 219: 15-25.

[13] Ning, Y., Wong, Y. S., Fuh, J. Y. H., and Loh, H.T. 2006. An approach to minimize build errors in direct metal laser sintering. *IEEE Trans Autom Sci Eng* 3: 73-80.

[14] Manetsberger, K., Shen, J., and Muellers, J. 2003. Compensation of non-linear

shrinkage of polymer materials in selective laser sintering. *In Proceedings of the SFF symposium,* 346-356.

[15] Jacobs, P. 2000. The effects of random noise shrinkage on rapid tooling accuracy. *Mater Design*, 21: 127-136.

[16] Wang, X. 1999. Calibration of shrinkage and beam offset in SLS process. *Rapid Prototyping*, 5: 129-133.

[17] Jain, P. K., Pandey, P. M., Rao, and P. V. M. 2008. Experimental investigation for improving part strength in selective laser sintering. *Virt phys prototyping*, 3: 177-188.