Tailoring Material Properties in Layered Manufacturing

Prashant K. Jain, Pulak M. Pandey and P. V. M. Rao

Abstract— **This paper discusses an approach for tailoring material properties in parts fabricated using Layered Manufacturing (LM). Solid model of the part is subdivided into various sub regions based on stress analysis. All subdivided regions are fabricated together by using Rapid Prototyping with process parameter values assigned as per their stress values. As mechanical properties are varying with process parameters and hence fabricated part will have customized mechanical properties for different regions. Commercial software MIMICS® is used to convert Magnetic Resonance Imaging (MRI) and Computer Tomography (CT) scan data, which is similar to data required in LM process. In the present work, it was observed that, this software can be best utilized for generating solid model from JPG images obtained through FEM analysis, for customizing mechanical properties. Various issues in implementing this, have been discussed and a case study of crane hook part is presented to demonstrate implementation procedure.**

Index Terms—**Rapid Prototyping, Selective Laser Sintering, Tailoring Material Properties, Computer Aided Design, Computer Aided Manufacturing.**

I. INTRODUCTION

It has been well established in literature [1-11] that material properties are directly related to process parameters in Selective Laser Sintering (SLS) process and hence can be varied by varying process parameters. Being SLS a layer by layer deposition process, material properties can be varied on each layer. This can be utilized as a potential advantage in Layered Manufacturing (LM) over other manufacturing processes to achieve distinct material properties in different regions. A novel methodology for tailoring material properties in different region of a layered part has been developed and demonstrated in this article. Developed methodology has been proposed for SLS process however it can be used for other LM process once the relations among process parameters and material properties are known.

Presently commercial SLS machines provide many scanning options for different requirements as discussed in next section but there is no option to assign different process parameters for different regions on same layer of a part. However different parameters can be assigned for different

Manuscript received October 30, 2009. Accepted for publication on February 02, 2010.

Prashant K. Jain was with Indian Institute of Technology Delhi, India as research scholar. He is now with Indian Institute of Information Technology Design and Manufacturing Jabalpur, Jabalpur M.P., India as assistant professor (e-mail: pkjain@iiitdmj.ac.in).

Pulak M. Pandey is the corresponding author of this manuscript. He is with Department of Mechanical Engineering of Indian Institute of Technology Delhi, NewDelhi, India (phone: 91-11-26596083; e-mail: pmpandey@mech.iitd.ac.in).

P. V. M. Rao is with Department of Mechanical Engineering of Indian Institute of Technology Delhi, NewDelhi, India (e-mail: pvmrao@mech.iitd.ac.in).

parts on same layer. In the present work it is realized that there is a need to propose a scanning strategy which can accommodate different process parameters in different regions of a layer hence can vary the properties in selected areas of a layer. These regions can be decided based on strength or stiffness requirements and may be obtained by Computer Aided Engineering (CAE) analysis.

II. SCANNING STRATEGIES AVAILABLE WITH COMMERCIAL SLS MACHINES

Many scanning options are provided in commercial SLS machines which include sorted-unsorted, hatch pattern along X, Y, both in XY and alternating in XY for different requirements [12]. Some machines also have up-down skin option to improve mechanical properties by allowing user to assign different process parameters at adjoining layers. Subsequent paragraphs discuss salient features of scanning strategies available with SLS process.

A. Skywriting

During scanning a certain time is needed to accelerate the mirrors to the desired speed. This is due to inertia of mirrors used for scanning. During this time laser beam cover some distance in which speed is not constant hence more energy is applied at the edges of the part than the inside of the part. To avoid this situation and to keep acceleration and retardation phase out of the layer geometry, skywriting option is provided in commercial SLS machines. If skywriting option is selected, then the mirror is accelerated already before the start of the part so that it has reached the desired speed before the beginning of exposure. Laser is switched on at the start of the part. Similarly retardation phase begins at the part end where the laser is switched off as shown in Figure 1.
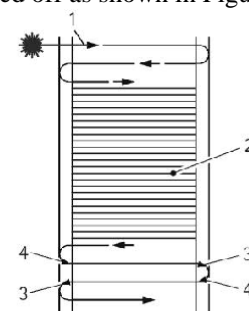
1 Direction of the exposure by the laser   3 Retardation phase
2 Building area, hatch lines   4 Acceleration phase

Figure 1: Skywriting scanning option [12]

B. Sorted unsorted

Whereas the unsorted strategy (Figure 3) moves the ebam across the part in a simple way, the sorted strategy (Figure 2) searches the shortest exposure path across the part,. The sorted exposure type is usually faster than the unsorted type but it may lead to gaps or slight recesses between first and second exposure phase as shown in Figure 2.
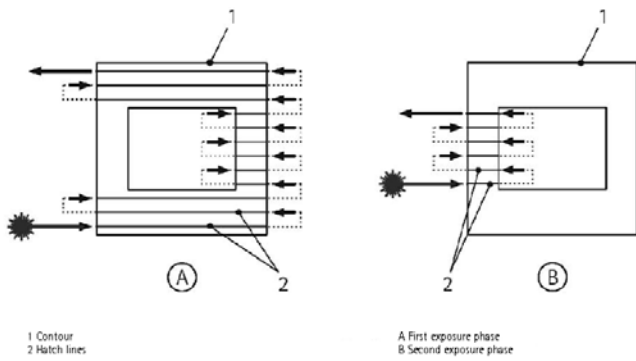
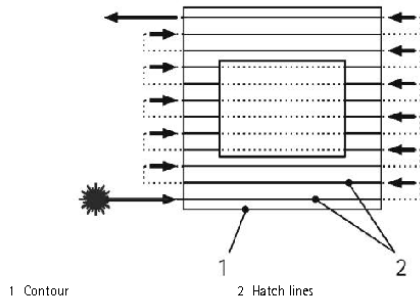Figure 2: Sorted scanning strategy with skywriting [12]

Figure 3: Unsorted scanning strategy with skywriting [12]

C. Hatch pattern

Four choices for hatch pattern selection are generally available, i.e., along X, along Y, both in X & Y or alternating in X & Y as shown in Figure 4. Scanning can be done either along X or along Y. If both in X & Y option is selected than there will be double exposure on the layer, once along X and then along Y. In alternating in X & Y choice, direction of scanning is changed for alternating layers.
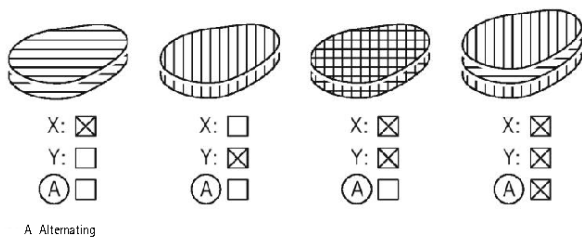
Figure 4: Various hatch patterns [12]

D. Up-down skin

Area on part layer, above which there is no area to be exposed is termed as up-skin. Similarly area on part layer, below which there is no exposed area called as down-skin. An area is termed as in-skin, where there is above and below exposed areas as shown in Figure 5. Commercial machine software calculates up-skin, down-skin and in-skin areas and different parameters can be assigned for these areas. Some overlapping area between in-skin and up-down-skin area can also be assigned for improved joint among these areas.
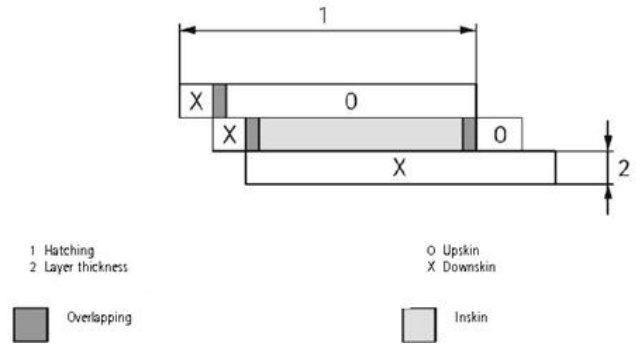
Figure 5: Up-down skin option [12]

III. METHODOLOGY FOR TAILORING MATERIAL PROPERTIES

In this work a novel approach has been proposed to achieve customized material properties for selected regions using SLS process. The proposed method facilitates fabrication of prototypes by considering stress pattern for improved material properties in critical regions. To implement this, solid model of the part is divided into various sub-parts based on stress levels obtained from finite element analysis (Figure 6). Images of stress patterns for each layer similar to RP process are stored as jpg images using FEM software. These images have been used to regenerate solid model of various subparts using commercial software MIMICS. Different sub-parts have been fabricated with different process parameters to vary mechanical properties in different regions with some overlapping area to ensure proper strength of the joint between subparts. This enables user to apply different process parameters for single layer (Figure 7). Developed methodology can reduce weight of parts by applying low energy density and faster prototyping by applying higher laser velocity and scan spacing in non critical regions obtained by CAE analysis. Further the method can be used in design and fabrication of functionally graded materials.
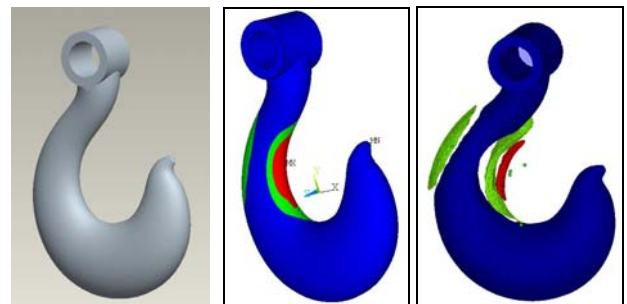
Figure 6: Solid model has been divided into distinct regions to tailor strength [13]

IV. IMPLEMENTATION PROCEDURE AND CASE STUDY

To describe the implementation procedure a case study of crane hook is presented here. Typical stress distribution for crane hook is obtained using FEM analysis and presented in Figure 8. Cross-sectional images of stress levels are retrieved at each section along the Z direction similar to the build direction in SLS process. Ansys Programming Design Logic (APDL) of ANSYS software is used to store cross sectional images of stress patterns for each layer are stored as jpg images. Procedure for storing stress patterns through APDL is presented in Figure 9. 2D cross sections of crane hook in

(revised on 28 December 2010)

XY plane along with stress values have been stored as jpg image (Figure 10). Further stress ranges can be chosen as per the requirements. In the present case three stress ranges have been considered as shown in Figure 11.
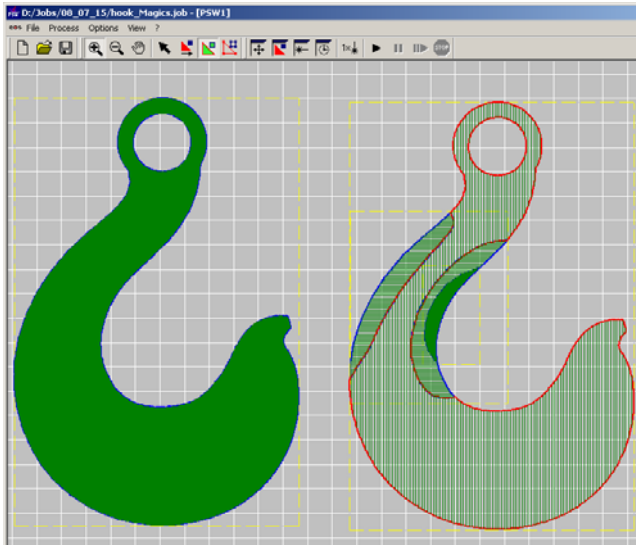

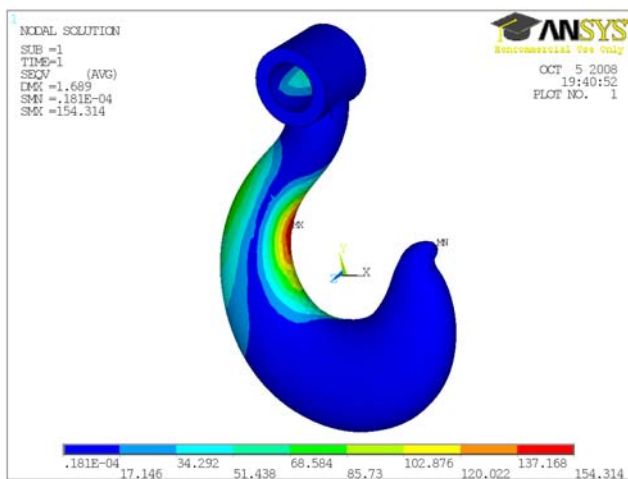Figure 7: Variation in scan spacing and hatch pattern on single layer [13]

Figure 8: Stress pattern obtained using ANSYS [13]

In the present work, commercial software MIMICS®, which is used to convert Magnetic Resonance Imaging (MRI) and Computer Tomography (CT) scan data into solid model, has been used to convert jpg images into solid model (Figure 13). However contour information for part fabrication can also be directly retrieved from jpg images. Recently Jain et. al developed such method using MATLAB Programming [13]. All images are imported in MIMICS software, Profile lines have been drawn and thresholding is used to separate out different colours in the jpg image (Figure 12). Region growing is used to join pixels of same colours on subsequent layers. Figure 13 shows cross sections of 3D solid model generated in three orthographic directions as well as in isometric view. Different solid models generated corresponding to each colour region is then exported as STL files. CLI file is generated corresponding to the STL files of these sub parts (solid models) using RP tools (commercial software for slicing) and then used for part fabrication. It is observed that file size of the re-generated STL files through MIMICS software is too large as compared to any other solid

modelling package. This is due to the region that software generates triangles by joining each pixel while writing STL file. It is also observed from the tessellated CAD model obtained from this method gives poor accuracy and surface finish (refer Figure 14 & 15). Which is further observed in fabricated part as shown in Figure 16.
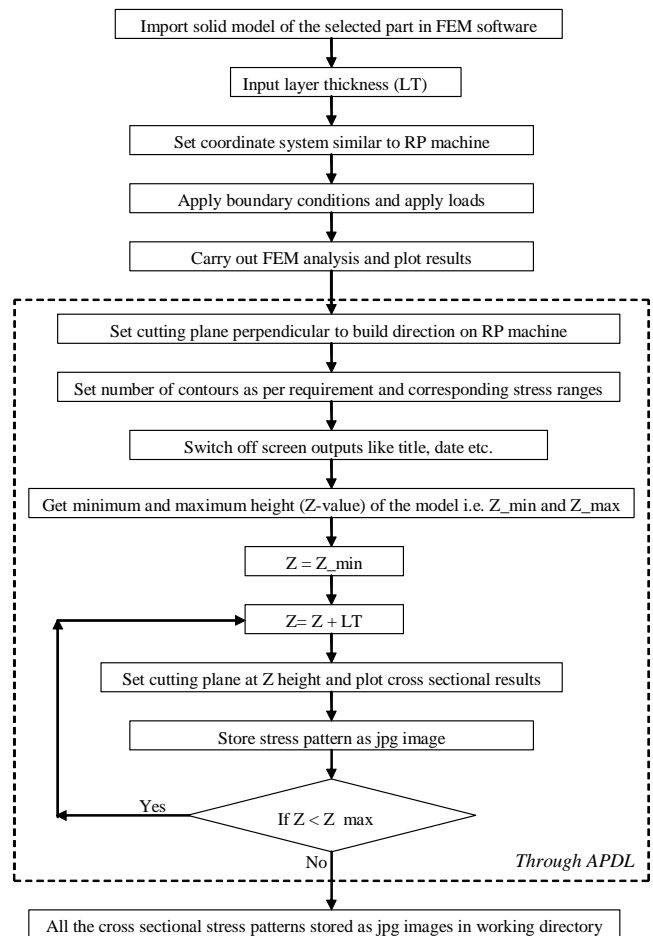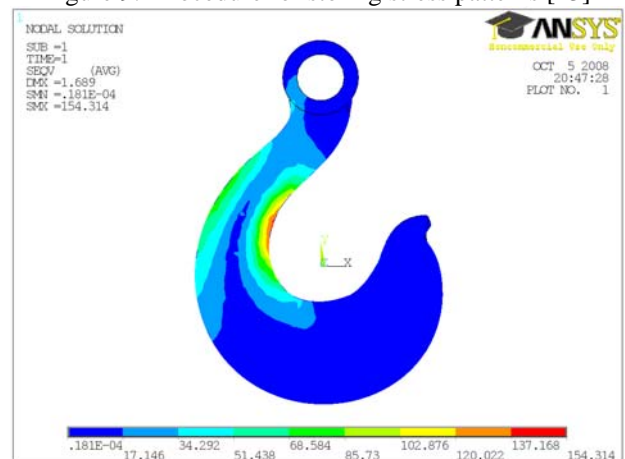

Figure 9: Procedure for storing stress patterns [13]

Figure 10: Stress distribution on a section at known Z-height stored as jpg image [13]
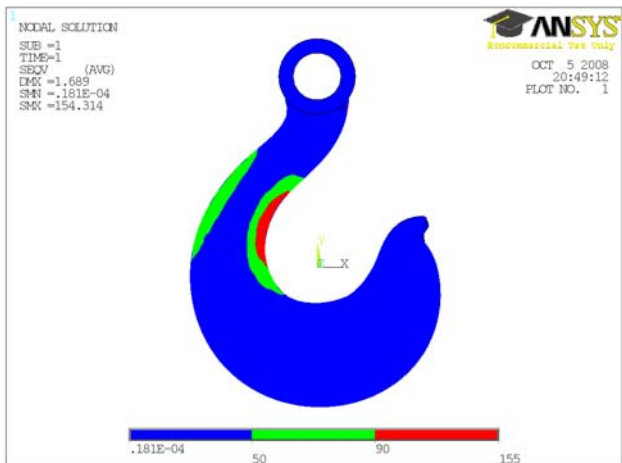
(revised on 28 December 2010)

Figure 11: Stress ranges are limited to three values [13]
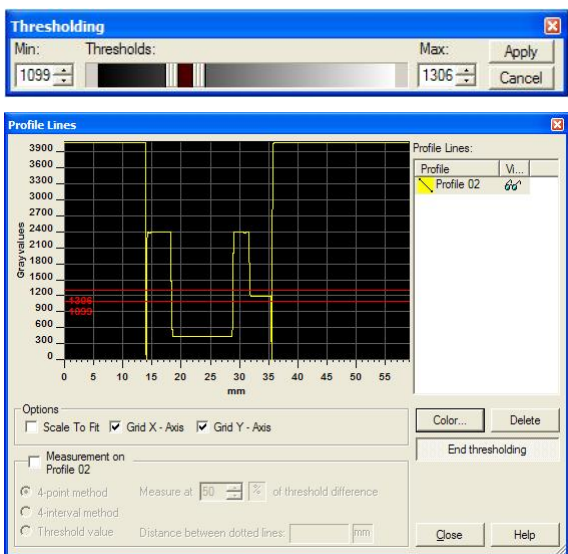
Figure 12: Thresholding using profile line
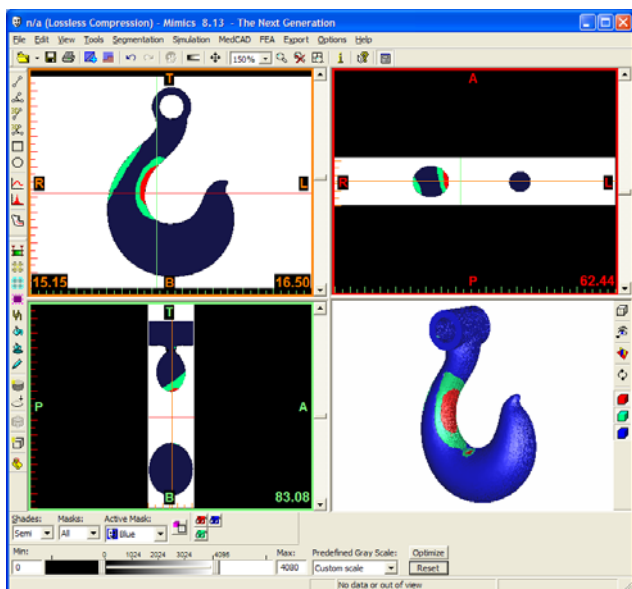
Figure 13: Solid model regenerated in MIMICS software

scanned in two steps to save the scanning time. Similar procedure is used in up-down
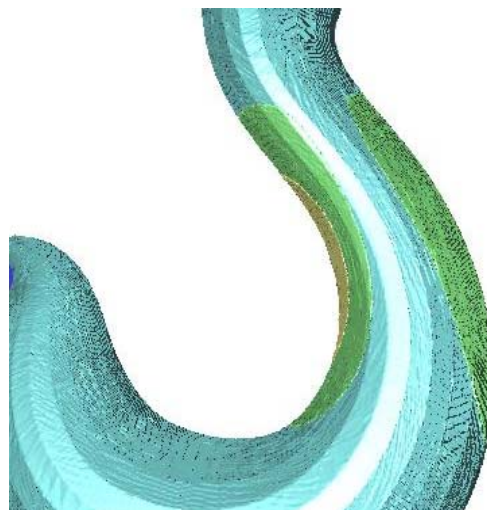
Figure 14: Accuracy loss in CAD model generated through MIMICS software
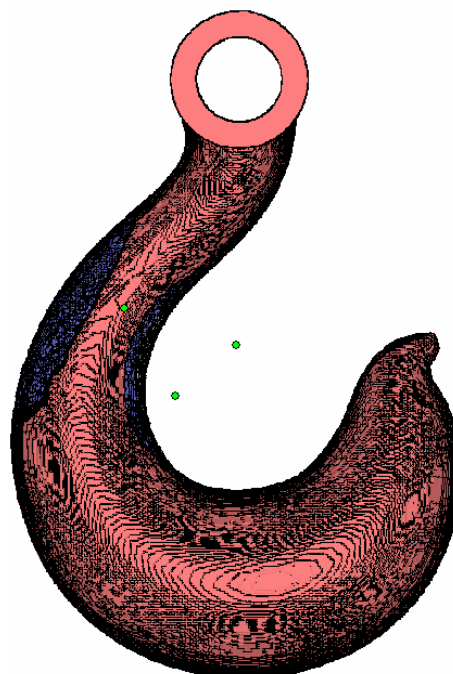
Figure 15: Poor surface quality observed on virtual parts generated through MIMICS software

Figure 16: Fabricated crane hook

While fabricating these crane hooks after dividing in three subparts, the issue of strength at the joint may requires exploration. However in this work it has been found that time lag between laser scanning for three parts on a layer is very less and does not affect the strength at joints. It is similar to sorted scanning strategy (Figure 2), where a contour is

(revised on 28 December 2010)

skin strategy where different parameters are assigned for up and down skin and are scanned separately with some overlapping area (Figure 5). However it is recommended that separate regions on a single layer can be laser scanned with some overlapping area to further enhance the strength of joint between sub parts.

V. CONCLUSIONS

The possibility of use of commercial software to tailor mechanical properties of LM parts has been demonstrated in the present work. A procedure to vary local strength or density of parts by varying process parameters has been implemented successfully by using MIMICS software. The proposed methodology of material properties tailoring for part fabrication can be used for many applications.

The developed methodology can be used to vary energy density in selected regions, based on stress analysis therefore reduced weight and cost can be achieved. Prototypes can also be built faster by applying higher values of laser velocity and scan spacing in non critical regions. New applications of LM processes may be found in fabricating heterogeneous objects or producing artifacts with desired porosity for biomedical application. Proposed methodology can be further exploit to fabricate functionally graded materials.

In this work it has been found that there may be limitations in using commercial softwares as accuracy loss has been observed because of tessellation used by MIMICS software. Therefore authors have extended this work and developed a novel approach [13] to implement the proposed frame work using MATLAB in which tessellation has been avoided.

REFERENCES

[1] Ajoku, U., Hopkinson, N. and Caine, M., 2006. Experimental measurement and finite element modelling of the compressive properties of laser sintered nylon-12, Materials Science and Engineering A, 428, 211–216.

[2] Caulfield, B., McHugh, P.E. and Lohfeld, S., 2007. Dependence of mechanical properties of polyamide components on build parameters in the SLS process, Journal of Materials Processing Technology, 182, 477–488.

[3] Chatterjee, A. N., Kumar, S., Saha, P., Mishra, P. K. and Choudhary, A. R., 2003. An experimental design approach to selective laser sintering of low carbon steel. Journal of Material Processing Technology, 136, pp. 151-157.

[4] Gibson, I. and Shi, D., 1997. Material properties and fabrication parameters in selective laser sintering process, Rapid Prototyping Journal, 3(4), 129-136.

[5] Jain, P.K., Senthilkumaran, K., Pandey, P.M., and Rao, P.V.M., 2006. Advances in Materials for powder based rapid prototyping, Proceedings of international conference on Recent Advances in Materials and Processing, at PSG College of Technology, Coimbatore, India, December 15-16, section 14.6.

[6] Tontowi, A.E. and Childs, T.H.C., 2001. Density prediction of crystalline polymer sintered parts at various powder bed temperatures, Rapid Prototyping Journal, 7(3), 180-184.

[7] Williams, J.D. and Deckard, C.R., 1998. Advances in modelling the effects of selected parameters on the SLS process, Rapid Prototyping Journal, 4(2), 90-100.

[8] Zarringhalam, H., Hopkinson, N., Kamperman, N.F. and De, J. J., 2006. Effects of processing on microstructure and properties of SLS nylon 12, Materials Science and Engineering: A, (435–436), 172–180

[9] Jain, P.K., Pandey, P.M., and Rao, P.V.M., 2008. Experimental investigations for improving part strength in Selective Laser Sintering, Virtual and Physical Prototyping, 3(3), pp. 177-188.

[10] Jain, P.K., Pandey, P.M., and Rao, P.V.M., 2008. Effect of delay time on part strength in Selective Laser Sintering, accepted for publication in International Journal of Advanced Manufacturing Technology, August 2008. (DOI: 10.1007/s00170-008-1682-3)

[11] Jain, P.K., Senthilkumaran, K., Pandey, P.M., and Rao, P.V.M., 2008. On the strength and accuracy of SLS prototypes, Proceedings of Indo-Russian workshop on Topical Problems in Solid Mechanics, Organized by DST, New Delhi and Russian Foundation for Basic Research, Russia at BITS Goa campus, November 7-11, pp. 283-298.

[12] EOSINT P380, 2003. Basic Training Manual, EOS Gmbh, Munich, Germany.W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.

[13] Jain, P.K., Pandey, P.M., and Rao, P.V.M., 2010. Tailoring Material Properties in Layered Manufacturing, Materials and Design, 31(7), pp. 3490-3498.

(revised on 28 December 2010)