Sindh Univ. Res. Jour. (Sci. Ser.) Vol.45 (3) 615-621 (2013)

SINDH UNIVERSITY RESEARCH JOURNAL (SCIENCE SERIES)

Selective laser sintering technique in fabrication of custom-made foot orthoses: A cost benefit analysis

JUMANI M S., SADIQ A SHAH, SHAKEEL SHAIKH

Assistant Professor, Department of Industrial Engineering and Management, Mehran UET, Jamshoro, Sindh, Pakistan
Email: jumanisaleh@hotmail.com

Abstract: Selective laser sintering (SLS) is one of the techniques in group of new manufacturing technologies that have emerged over last 15 years. These techniques works on principle of creating three-dimensional (3D) parts form computer aided design (CAD) information by addition of layer by layer on top of each other. The process is called additive manufacturing (AM). In medical sector application of these techniques are gaining more importance for fabrication of custom-made devices and rehabilitation aids. Foot orthosis is custom-made device applied to patients suffering form foot problem, congenital defects and diseases including arthritis and diabetes. This paper presents the findings from the cost and lead-time analysis performed using selective laser sintering technique as an alternative route for fabrication of custom-made foot orthoses. The results showed that selective laser sintering is an economical method for fabrication of foot orthoses. Furthermore, it has also to be underlined that material and machine cost of additive manufacturing techniques in general and SLS specially is still higher in comparison to traditional orthoses fabrication techniques

Keywords: Additive manufacturing, Foot orthoses, Cost modelling, Lead-time modelling

INTRODUCTION:

Rapid manufacturing evolved from rapid prototyping (RP) techniques which use different fabrication processes including extrusion, sintering and other methods of deposition of material layer by layer over one another to form 3D parts. These techniques require no tooling and fixtures and involve less labour content during the fabrication process [1]. The significant advantages of the techniques are increased design freedom and ability of fabricating virtually complex geometrical parts, hollow structures and undercuts in the parts [2]. This has given the designers more freedom in designing of complex geometrical parts. Some of the well established rapid manufacturing techniques are stereolitho-graphy (SLA) fused deposition modelling (FDM), 3D printing (3DP) and selective laser sintering (SLS). Applications of the techniques are increasing and can be observed in manufacturing sectors including automotive, toys, defence, aero industry and medical sector [3-4].

In medical sector the need of personalised devices, rehabilitation aids and parts to suit and fit individual anatomies is explicit [5]. The ability of fabricating the individualised complex geometrical devices has increased the use of these techniques for production of custom-made devices and parts in this sector. There are two successful commercial examples of production of personalised dental prosthesis produced by Align technologies Inc USA and in-the ear-hearing aids by Siemens GMBH, Germany [6-7]. Figure 1 shows the dental brace and in-the ear-hearing aid.

Fig.1:Dental brace and in-the ear-hearing aid produced through RM techniques

Foot orthosis is medically prescribed device for treatment of foot problems, congenital defects, sports injuries and foot defects occurred through diseases including rheumatoid arthritis and diabetes [8-10].

Corresponding Author: jumanisaleh@hotmail.com

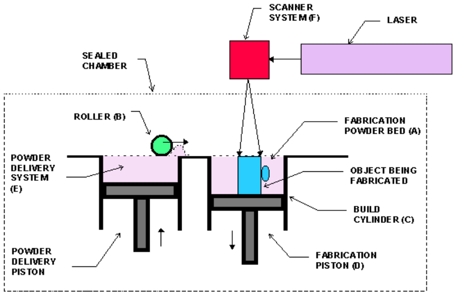
Figure 2 shows the custom-made foot orthoses fabricated for support for foot arch.

Custom-made orthoses has long history of handcraft art to computer aided design and computer aided manufacturing (CAD/CAM) techniques. The traditional handcraft techniques are based on trial and error method in which fabrication process starts with foot geometry capture using plaster of Paris. After then a positive mould is developed which is corrected manually by adding some material on the developed mould in order to incorporate required orthoses design features. The orthosis is then created around the mould by draping of heated plastic sheet to get the desired shape of the orthoses [11]. With the introduction of computers in manufacturing engineering CAD/CAM techniques were introduced [12]. In CAD/CAM the fabrication process starts with foot impression capture using 3D foot geometry capture device. The captured foot impression is then modified with specific orthoses design software through CAD system. Finally the CAD based designed orthoses is fabricated through numerically controlled (NC) machines [13-14].

Fig.2: Foot orthoses designed for arch support

3. Selective laser sintering (SLS) technique

Selective laser sintering (SLS) technique creates three-dimensional solid parts by selectively fusing powder material with CO2 laser, turning powder material into solid objects. Figure 3 represents the schematic of the SLS process. The powdered material is spread on the bed (A) by a roller (B) over the surface of build cylinder (C). Powdered material is then sintered or melted by CAD guided laser beam (F) that selectively scan the surface of the powder bed, melting the powder and creating a two dimensional solid layer. When the first layer is completed, the build platform piston (D) moves down and another layer of powder material is deposited on the fabrication bed (A) from the powder delivery system (E) by roller on the top of previously formed layer. The process is repeated until the part or object is completely formed [15]. In this process the fabrication chamber is maintained at a temperature just below the melting point of the powder material so that heat from laser only needs to raise the temperature slightly to cause sintering [15-17]. This makes the process of fabrication of the part or object quicker. After completion of fabrication process the part is removed from the building chamber of the machine.



Fig,3: Schematic of selective laser sintering technique (additive3d.com, 2012)

4 METHODOLOGY

4.1 Specifications of the CAD based orthosis model and material used

A CAD based orthosis model shown in Figure 4 was used to fabricate the orthosis model through selective laser sintering technique. The designed orthosis model was adopted from the work of Pallari [18] for mass customisation of foot orthoses for rheumatoid arthritis. Table 1 show the specifications of the orthosis model and build time for fabrication of orthosis model.

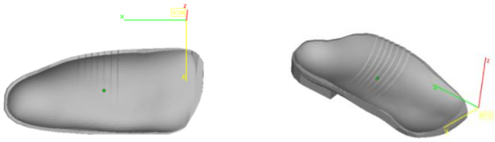


Fig. 4: CAD based orthosis model

Specifications of orthosis model	
Orthosis measurements	Height 50.82, Width 179.52, Depth 79.81 mm
Build time	16 hours
Material	Duraform PA

Table 1: Specifications of orthosis model and material consumed

4.2 Fabrication of orthosis model

The *spro* 60 SD SLS system in selective laser sintering technique was used to fabricate the orthosis model. The CAD based orthosis model shown in Figure 4 was converted into .stl file format. The final orthosis design in .stl format was sent to the selective laser sintering system. The SLS machine was assumed to work for one run of 16 hours of build time per day working for 220 days per year. Production volume per year was calculated by estimating the total production volume per year from the model. It was estimated that from one run of 200 mm build height on average 30 parts or 15 pairs of orthoses can be fitted. The build time of 16 hours per run was given by the build setup^{TM} machine controlling software. The machine was assumed to work for 220 days per year which gives a total of 3520 machine operation hours per year; approximately 40% of machine utilisation time per year.

5 RESULTS AND DISCUSSION

5.1 Cost and lead-time modelling

In SLS technique using *spro* 60 SD SLS system one machine was assumed to work for one run of 16 hours of build time per day working for 220 days per year. Production volume per year was calculated by estimating the total production volume per year from the developed model. Table 2 shows the estimated total cost of £363360 for fabrication of 3300 pairs per year at the rate of £110.10 per pair. Machine cost per year was calculated by depreciation cost of machine and 10% of actual cost of machine as the maintenance cost per year. The depreciation time for machine was set for 5 years. This gives an estimated total of £75000 as the machine cost per year. Material cost per pair was calculated in terms of sintered material per build by weighing the fabricated parts and unsintered material per build by calculating the volume of unused material and multiplying it by unsintered material density. This gives an estimated material cost of £64 per pair. Production overhead per year was calculated by floor space cost at the rate of £120/m^2 per year. This cost was added with cost of energy for machine at the rate of £1.5 per hour [19]. This gives an estimated total of £34860 per year as production overhead. A uniform administrative overhead per year at the cost of £2320 was included in the model.

Labour cost was calculated by required labour time for operation of machine; based on one hour of time for setting of machine and loading of material and 2 hours of time for cleaning the fabricated parts. The operation of one run on *spro* SD 60 SLS system requires 3 hours of labour time of the technician. However, in the initial cost model, labour cost of £39980 is included as the annual salary of the technician.

Cost calculations using *ipro* SD 60 system in SLS technique		
Production volume per year		
Number of parts/build	N	30
Build time/run	T	16 hours
Production rate/hour	R = N/T	1.87
Operation hours/year	HY	3520
Total production volume/year	V = R x HY	6600 parts
Total pairs/year		3300 pairs
Machine cost per year		
Machine and ancillary equipment	E	£250000*
Machine depreciation cost/year	D = E/5	£50000
Machine maintenance cost/year	M	£25000
Total machine cost/year	MC = D+M	£75000
Material cost per pair		
Material cost	per kg	£64/kg***
Volume of each part cm^3	83596 mm^3	83.59 cm^3
Mass of each part	83.59 cm^3 x 0.6g/cm^3= 50.15g	0.050 kg
Mass of sintered material/build	(30 x 83.59 cm^3) x 0.6g/cm^3 =1504.62g	1.50 kg
Mass of unsintered material/build	(25146 cm^3-30 x 83.59 cm^3) x0.6g/cm^3	13.50 kg
Cost of material used/build	(1.50 kg + 13.50 kg) x £64/kg	£960
Material cost/part	£960/30 parts per build	£32/part
Total cost/pair		£64/pair
Production overhead per year		
Building area	246.5/m^2 @ £120/m^2/annum**	£29580

Energy consumption by machine	@£1.5/hour x 3520 machine operation hours/year from operating model	£5280
Total cost/year		£34860
Administrative overhead per year		
Hardware purchase	one of cost	£2175*
Software purchase	one of cost	£2175*
Consumables cost/year		£1450
Hardware depreciation cost/year		£435*
Software depreciation cost/year		£435*
Total cost/year		£2320
Labour cost per year (annual salary of operator)		£39980
Total cost	3300 pairs/year	£363360
Cost/pair	£363360/3300 pairs	£110.10

*, ** Ruffo et al, 2006 and *** Cost quotation from system and material supplier, Laser Lines Limited UK, 2010.

Table 2 Cost calculation using *spro* SD 60 SLS system

5.2 Sensitivity analysis of the model

Scenario 1-Increasing the machine operation hours per year

The initial operating model is sensitive to any variation or change in different parameters such as increasing the machine operation hours per year. This subsequently increases the total number of runs per year, labour and material costs resulting in increased production volume per year.

The initial operating model based on 220 working days per year was assumed to work for 365 days per year. Table 3 shows the cost categories in assumed initial operating model working for 365 days per year. A part time technician working for 3 hours of time per day for 145 days was included. The model has increased the production volume from 3300 pairs to 5475 pairs per year at the rate of £94.23 per pair. This has reduced approximately 15% in total cost per pair compared to initial operating model based on 220 working days per year.

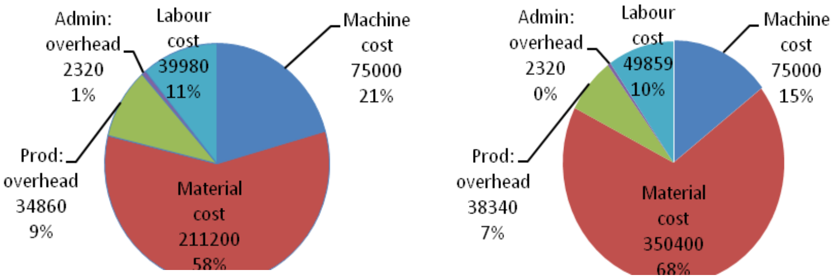
.

Total cost per pair using *spro* 60 SD SLS system		
Machine cost per year		£75000
Material cost for 5475 pairs	@£64 per pair	£350400
Production overhead per year		£38340
Administrative overhead per year		£2320
Labour cost per year	Full time + part time operator	£49859
Total cost per year	5475 pairs per year	£515919
Cost per pair	£515919/5475 pairs	£94.23

Table 3Total cost per pair in initial operating model based on 365 working days per year

Figure 5 shows the detailed breakdown of different cost elements in the initial operating models based on (a) 220 and (b) 365 days per year. The indirect costs account for 42% and 32% of the total cost respectively. This includes machine cost 21%, 15%, production and administrative overheads 10%, 7% and labour cost 11%, 10% of the total cost. Material cost accounts for 58% and 68% of the total cost as the direct costs in the models

.



(a) (b)

Figure 5 Cost categories in initial operating model based on 220 and 365 working days per year

Scenario2-Development of low cost operating model

A low cost operating model was developed based on one run of 16 hours of build time per day working for 365 days per year. The developed model is based on 5 technicians working with 8 machines in order to obtain optimal productivity by balancing the required labour hours per year for machines and labour hours of technicians per year. In the model one machine was assumed to work for one run of 16 hours of build time per day for 365 days year. This gives 5840 machine operation hours per year for one machine; approximately 66% machine utilisation time per year.

Table 4 shows the operation hours of machines per year and labour hours per year for technicians in the low cost operating model. The operation of one run on one machine requires 3 hours of labour time. The operation of 365 runs on one machine requires a total of 1095 machine labour hours per year. This gives an estimated total of 8760 labour hours per year required for operation of 8 machines. The labour hours for one technician are based on 1760 labour hours per year which gives a total of 8800 labour hours per year for 5 technicians. The operating model was assumed to fabricate a total of 5475 pairs per year on each machine, which gives an estimated annual production volume of 43800 pairs per year.

No: of machines	Total required machine labour hours per year	No: of technicians	Total No: of technicians labour hours per year
1	1095	1	1760
2	2190	2	3520
3	3285	3	5280
4	4380	4	7040
5	5475	5	8800
6	6570	6	10560
7	7665	7	12320
8	8760	8	14080
9	9855	9	15840
10	10950	10	17600

Table 4 Machine labour hours/year and technicians labour hour/year in “best case” cost model

Table 5 shows details of cost categories in low cost model. A floor space of 20m^2 at the rate of £120/m^2 for each machine and energy consumption cost of £1.5 per hour for each machine is included. This is added with the machine purchase and operation cost of 8 machines and material consumption cost of £2803200 per year. The labour cost for 5 technicians is estimated for £199900 per year at the rate of £22.71 per hour. The model gives an estimated total of £3738120 for fabrication of 43800 pairs per year at the rate of £85.34 per pair; approximately 23% reduction in cost per pair compared to initial operating model based on 220 working days per year.

Low cost operating model for 5 technicians working with 8 machines		
Machine cost per year for 8 machines		£600000
Material cost for 43800 pairs	@£64 per pair	£2803200
Production overhead per year for 8 machines		£116460
Administrative overhead per year for 8 machines		£18560
Labour cost for 5 technicians		£199900
Total cost for 43800 pairs		£3738120
Cost per pair	£3738120/43800 pairs/year	£85.34

Table 5 Total estimated fabrication cost per pair in "best case" SLS cost model

Figure 6 shows breakdown of different costs in low cost operating model. In the total cost, material cost accounts for 75% as the direct cost in the model. The indirect costs account for 25% of the total cost. This includes machine cost 16%, production and administrative overheads 4% and labour cost 5% of the total cost as the indirect cost in the model. The total estimated fabrication per pair cost of £85.34 can be further reduced by reuse of unsintered material in the build. According to Duraform material guide by 3D systems unsintered material can be used not exceeding 67% with the ratio of total material (Guide to Duraform materials, 3D Systems, Inc, USA, 2002). Swell and colleagues have experimented that five time reuse of unsintered Duraform PA material does not compromise overall material properties and strength [21]. The work in this research is focused on modelling the cost of foot orthoses per pair using selective laser sintering technique. In the work the cost per pair for foot orthoses is estimated through full costing concept that includes machine, material, labour and production and administrative overheads. However; for ROI calculations, generation of business models; that involve some statistical methods and techniques are required that was out of the scope of this research.

Conventional fabrication techniques require high skill labour which is a major cost increasing element. However, in the selective laser sintering technique, the burden of labour cost is transferred to the technology itself i.e., the rapid manufacturing systems [4]. The SLS technique involve minimum human interferences during the fabrication process due to the automated fabrication process and have the advantage of minimal requirements of skills and labour of the operator [6]. All these factors subsequently reduce the labour costs and overall manufacturing costs in the system. The cost of material is the major cost incurring element which increases the total cost per pair in the model. However, the commercialisation of rapid manufacturing techniques and materials are progressing at rapid rate with respect to improvements in the processing techniques and materials which may subsequently bring down the costs of systems and materials

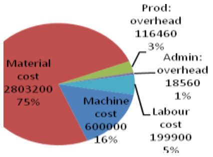


Fig.6: Cost categories in "best case" cost model

6. CONCLUSION

Selective laser sintering technique in fabrication of custom foot orthoses generates a digital design and manufacturing process. The process involves digital foot impression capture technique and digital orthoses design system combined with digital fabrication process which gives increased accuracy in measurements of foot geometry, orthoses design features by reducing errors during the manual correction and modifications process and the digital fabrication process minimise the part errors. This subsequently produces accurate clinically effective and improved fit for enhanced performance form the custom made foot orthoses. The cost model gave the cost of £85.34 per pair using SLS technique in comparison to present cost of custom foot orthoses in the market, where one pair of orthoses costs approximately rages from £150 to £200 (www. doctorsorthotics, 2013). One of the other significant challenges in the market is the lead-time which is normally ranges from 7 to 14 days depending on the manufacturer. At present the orthotics industry however is predominantly small companies, who do not always have access to large amounts of capital. At present the cost of rapid manufacturing machines and material are still higher. As the applications of SLS technique is increasing worldwide in different manufacturing sectors; more efficient and faster machines and low cost materials could be introduced which will contribute in more cost-effective fabrication of custom made devices and rehabilitation aids in the orthotics and prosthetic industry.

REFERENCES

Brocklesby S, Wooles C. Cost comparison: orthoses an audit. In-house manufacture from sheet materials versus prefabricated orthoses. (2009) Podiatry Now. Vol. (6), 1, 17-23.

Caselli MA. Orthoses, materials, and foot function. (2004) Podiatry Management; Vol. (7): 2, 131-140.

Cormier Denis, Ola Harrison and Tushar Mahale., (2003) Rapid Manufacturing in the 21st Century, Journal of the Chinese Institute of Industrial Engineers, Vol. (20): 3, 193-202.

Czajkiewicz, Z.J., (2008) "Direct Digital Manufacturing, New Product Development and Production Technology", Economics and Organization of Enterprise, Vol. (2): 2, pp 29-37.

Dalgarno, K. W, J. H. Pallari, J. Woodburn, K. Xiao, D. J. Wood, R. D. Goodridge and C. Ohtsuki, (2006) Mass customization of medical devices and implants: state of the art and future directions. Virtual and Physical Prototyping, Vol. (3): 137-145.

Doxey, Gordon E. (1985) Clinical Use and Fabrication of Molded Thermoplastic Foot Orthotic Devices Vol. (65): 11, 1679-1682.Gibson l D. W. Rosen l B. Stucker, (2010) Additive Manufacturing Technologies Rapid Prototyping to Direct Digital Manufacturing, Springer.

Grumbine N. Computer-generated orthoses. (1993) A review. Clinical Podiatry Medicine Surgery, Vol. (10): 3, 377-391.

Guide to Duraform Materials, 3D Systems, (2002), DCM 8002–10004–001.

Hopkinson, N., Hague, R. and Dickens, P., (2006) Rapid Manufacturing: An Industrial Revolution for the Digital Age. Chichester, England: John Wiley and Sons.

Lusardi, M.M, and Nielsen, C.C, (2000) "Orthotics and prosthetics in rehabilitation", Butterworth-Heinmann, ISBN 0750698071.

Pham D.T and R.S Gault, (1998) Comparison of rapid prototyping technologies, International Journal of Machine Tools and Manufacture, Vol. (38): 10-11, 1257-1287.

Pham, D. T. and S. S. Dimov, (2003) Rapid prototyping and rapid tooling- the key enablers for rapid manufacturing, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering, Vol. (217): 1, 1-23**.**

Pallari J., (2008) "Mass customisation of foot orthoses for rheumatoid arthritis," Ph.D. Thesis, Dept. Mech. Eng., Univ. Leeds, Leeds, U.K.

Ruffo M, C Tuck, and R Hague, (2006) Cost estimation for rapid manufacturing laser sintering production for low to medium volumes, Proceedings of the Institution of Mechanical Engineers, Part B: Vol. (220): B, 1417-1427

Sewell, N. T., M. Felstead, M. R. Sloan and M. A. Jenkins, (2008) "A Study of the Degradation of Duraform PA Due to Cyclic Processing," Virtual and Rapid Manufacturing, Advanced Research in Virtual and Rapid Prototyping, Taylor and Francis Group, London, ISBN, 9780-0-415-41602-3., 299-302.

Smith D and Burgess EM, "The use of CAD/CAM technology in prosthetics and orthotics-Current clinical models and a view to the future", (2001) Journal of Rehabilitation Research and Development, Vol. (38): 3, 327-334.

Staats Timothy B and Kriechbaum Michael P, (1989) Computer Aided Design and Computer Aided Manufacturing of Foot Orthosis. Journal of Prosthetic and Orthotics Vol. (1): 3, 182-186.

Tuck C.J., Hague R.J.M., Ruffo, M. Ransley M. and Adams P., (2008) Rapid manufacturing facilitated customisation, International Journal of Computer Integrated Manufacturing, Vol. (21): 3, 245-258.

Yan Xue and P Gu, (1996) A review of rapid prototyping technologies and systems Computer-Aided Design, Vol. (28): 4, 307-318.