Solid Freeform Fabrication 2016: Proceedings of the 27th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Statistical Process Control Application to Polymer based SLS process

S.O. Akande[ac], K.W. Dalgarno[a], J. Munguia[a], J. Pallari[b]
[a] *School of Mechanical and Systems Engineering, Newcastle University, Newcastle, UK*

[b] *Peacocks Medical Group Ltd., Newcastle, United Kingdom*
[c] *Kogi State Polytechnic, Lokoja, Nigeria*

Abstract

The quality of selective laser sintering (SLS) made parts is known to be influenced by process parameters and the quality of input material. In order to ensure consistency in part quality, there is a need to monitor the quality of parts made using the SLS machines. Benchmark specimens were designed and manufactured to track key quality characteristics of strength, bending stiffness, density and dimensional accuracy of parts made in multiple builds. Using data collected from the benchmark tests, correlation analysis and statistical process control (SPC) charts were established. SPC was found to be a useful tool that can provide SLS users with the mean of identifying possible changes in the process. Therefore, it can be used for process monitoring in SLS process to ensure consistency in part quality for long term production.

Keyword: quality control, statistical process control, lasers, sintering, polymer, impact strength

1. Introduction

Additive manufacturing (AM) is a manufacturing technology that enabled the production of products directly from 3D CAD models by material consolidation in layers without the need of tooling or jigs [1]. This has simplified 3D part production processes to 2D layering processes [2]. AM has also found application in various fields such as in the medical field for preoperational planning and craniomaxillofacial interventions [3] and the production of prostheses and orthotics [4, 5]. Selective laser sintering (SLS) is a powder based AM process and is one of the most important processes of AM that can be used to produce durable and functional parts. SLS has been used to directly manufacture functional parts like bespoke parts and small varieties of end use parts [6]. However, the ability to monitor SLS process performance is crucial importance in fabricating parts with good quality and is of major importance to repeatability in parts properties.

The SLS process uses a CO_2 laser to sinter selectively a thin layer of powder spread over a moving platform by heating it so that the surface tension between particles is overcome, resulting in fusion of the particles. A computer directs a laser scanning mirrors over the powder layer, sintering and bonding a new layer of the part [7]. Once a layer is completed the platform is lowered and a new layer of powder is spread over the previously sintered layer. These processes are repeated sequentially until the part is fully made [8].

However, quality of parts made by SLS machines have been observed by various authors to vary with builds, which was attributed to materials and process parameters [8-15].

Real time melt pool analysis and control to achieve desired quality through the use of feedback control system in powder based SLS processing technology was proposed by Berumen et al. [16] for metal parts. Krauss et al.[17] also used thermography for monitoring of process parameter deviation in selective laser melting. An online quality control system for selective laser melting by the use of systems for monitoring powder layers deposing and real time melt process has also been developed [18].

However, statistical process control (SPC) can be used to monitor, maintain and improve the capability of processes to assure product conformance [19]. Based on the SPC analysis informed decisions can be taken to maintain the quality of the product. SPC is therefore the voice of the process [20]. Control charts are an established SPC methodology[21]. SPC has been used in the manufacturing of medical accelerators and in weld process monitoring successfully [19, 22]. MacGregor and Kourti [23] also used SPC for online monitoring and diagnostic of continuous polymerization process. Previous work [24] has identified a set of benchmark for use in polymer SLS processes, in order to benchmark SLS machines for manufacturing of quality parts. The benchmark specimens were designed for manufactured and tested to tracked changes in key quality characteristics of strength, modulus, density and dimensional accuracy of specimens made in multiple builds [24]. In this paper, the application of statistical process control (SPC) charts to track the measurements across multiple builds is described.

2. Control charts

The control chart for measurement of characteristics (Shewhart) has been adopted in this work. These charts can monitor the process average $\left(\overline{X}\right)$ and process spread, known as the range (R) chart, and the standard deviation chart (S). However, $\left(\overline{X}-S\right)$ is less sensitive than $\left(\overline{X}-R\right)$ in detecting special causes of variation due to a single value in subgroup being unusual [25]. Range charts also give a more efficient estimate than the standard deviation when subgroup sizes are small [25, 26]. Thus, $\left(\overline{X}-R\right)$ was used in this study.

2.1.1 The mean control Chart

The averages of the subgroups, based on central limit theorem are expected to be normally distributed, irrespective of the individual measurement distribution from which the averages were calculated.

The action or control limits for the average chart is given as:

$$\mu \pm 3\hat{\sigma} \tag{1}$$

Where, μ is the group mean and $\hat{\sigma}$ is the standard effect or variation of the averages.

If for a particular variable we have n measurements per build, over k builds then the average within a build for that variable is computed by summing the n individual measured data and dividing them by the total number of measurement (n) for each build. The central line for the control chart is the arithmetic mean of all the averages. The mean and standard deviation is given by equations (3) and (4).

$$\overline{x_i} = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \tag{2}$$

$$\mu = \frac{1}{k}\sum_{i=1}^{k} \overline{x_i} \tag{3}$$

Where, $\overline{x}$ is the mean of individual data, n is the subgroup sample size (3 or 4 samples per build in this study), k is the subgroup numbers (11 builds in this study), $\overline{x_i}$ averages of the subgroups

The standard deviation of the averages $(\hat{\sigma})$ is given as:

$$\hat{\sigma} = \sqrt{\frac{k\sum_{i=1}^{k}\overline{x}_i^2 - \left(\sum_{i=1}^{k}\overline{x_i}\right)^2}{k(k-1)}} \quad (4)$$

2.1.2 Range control chart

The range of ith subgroup (R_i) is given as:

$$R_i = r_{max_i} - r_{min_i} \quad (5)$$

Where, r_{max_i} *and* r_{min_i} are the maximum and the minimum data in the ith subgroup.

The average of the range $\overline{R}$ is given by

$$\overline{R} = \frac{1}{k}\sum_{i}^{k} R_i \quad (6)$$

The control limits for the range chart is given as:

$$\text{Control limits} = \overline{R} \pm 3\hat{\sigma}_R \quad (7)$$

And it can also be expressed as [22]:

$$\text{Control limits} = \left((1 \pm 3d_3/d_2)\overline{R}\right) \quad (8)$$

Where, $\hat{\sigma}_R$ is the standard deviation of the range, $\overline{R}$ is the average of the ranges, k is the subgroup numbers in the experiment, d_2 *and* d_3 are constants of proportionality and are dependent on the size of the subgroup and can be found in various statistical books [21]. Furthermore, there are various rules in interpreting the control chart. The chart can be said to show evidence of assignable cause of variations when either of the following basic rules is violated [26]:

1. When a point is outside the action/control limits (±3 standard deviation).
2. When two successive points are outside the same warning limit (±2 standard deviation).

Wetherill and Brown [26] pointed out that other rules can be used for interpreting control charts but they increase the chance of raising false alarm. The presence of assignable causes of variations means that the sample is not part of population that is being estimated for mean and range or standard deviation [26]. Therefore, the process will need to be studied, to find out the cause of the variations with the aim of controlling it. The investigation and removal of variations are crucial in process improvement which can only come with increasing knowledge of the process.

3. Material and methods

The benchmark specimens used are illustrated in Figure 1. The benchmark specimens were made lying flat in the powder bed (with the thickness in Z, using conventional axes).

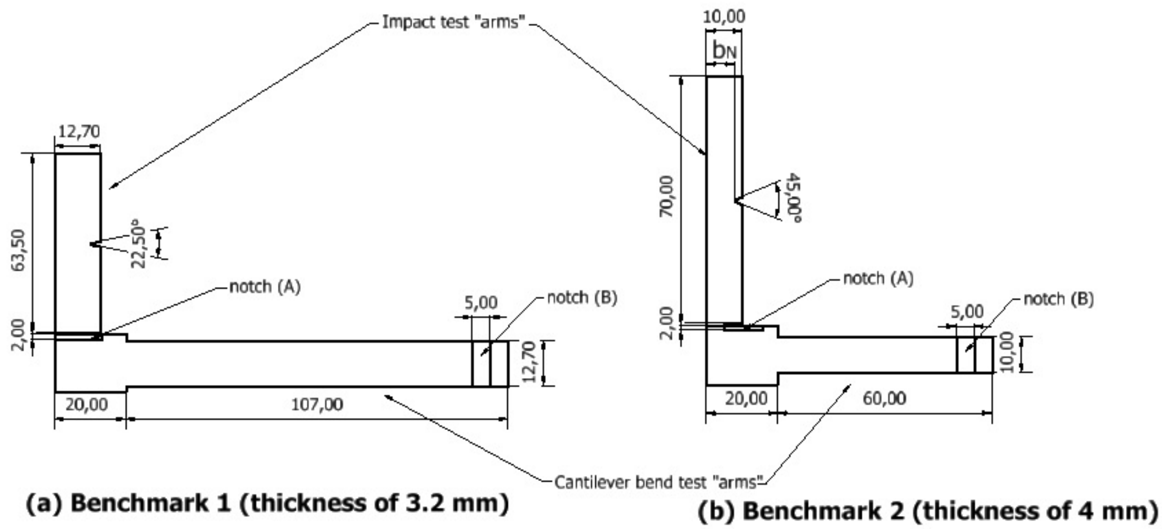

Figure 1 Benchmark specimens, from [24].

Specimens were made by Peacocks Medical Group in Innov PA 1350 ETx (Nylon 11) material supplied by EXCELTEC (France) using 3D Systems sProSD SLS machine, and with the processing conditions shown in Table 1. The first build was a virgin powder build which was used for machine calibration. Powder was then refreshed with a mix ratio of 29% virgin and 71% (cake and overflow) powders, with the same refresh ratio for all subsequent builds. Four of each benchmark specimen were produced as part of build 2, with 3 of each benchmark specimens then produced in builds 3, 4 and 6 to 13, which was the final build.

Table 1 SLS process parameters for parts supplied by Peacocks Medical Group

Equipment	3D Systems sPro60SD
Laser power	20 W
Outline laser power	7 W
Fill scan spacing	0.15 mm
Laser scan strategy	Sorted fill
Layer thickness	0.1 mm
Scan speed	5 m/s

At the end of each build the flexural modulus, impact strength, dimensional accuracy and density of the benchmark parts were measured using the techniques described in [24].

4. Results

4.1 SPC charts for benchmark flexural modulus

Figure 2 shows the SPC chart for flexural modulus of benchmark 1 and benchmark 2 specimens made in multiple builds.

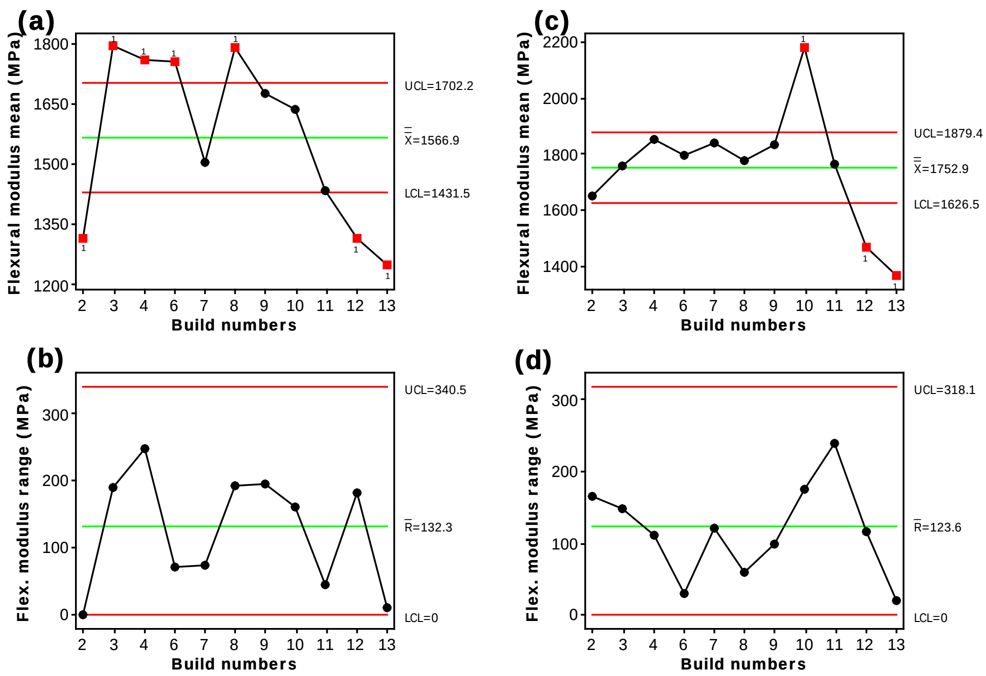

Figure 2 SPC flexural modulus mean and range charts for Benchmark 1 (a), (b) and for Benchmark 2 (c), (d)

4.2 SPC charts for impact strength

Figure 3 shows the SPC chart for impact strength of benchmark 1 and benchmark 2 specimens made in multiple builds.

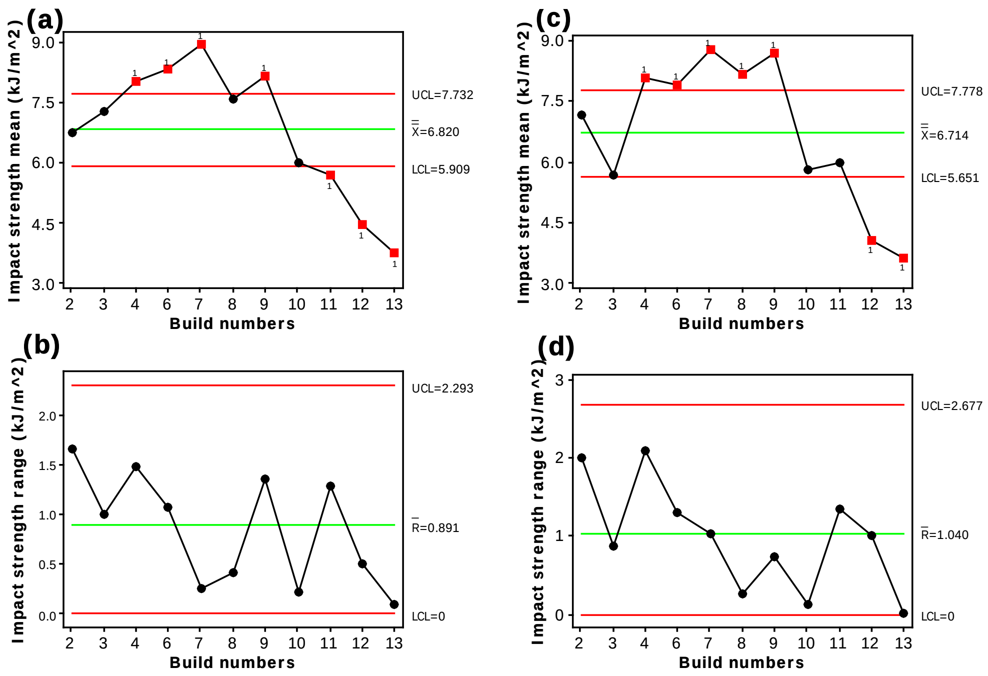

Figure 3 SPC Impact strengths Mean and range charts for Benchmark 1 (a), (b) and for Benchmark 2 (c), (d)

4.3 SPC charts for dimensional accuracy

Figure 4 shows the SPC chart for dimensional accuracy of benchmark 1 and benchmark 2 specimens made in multiple builds.

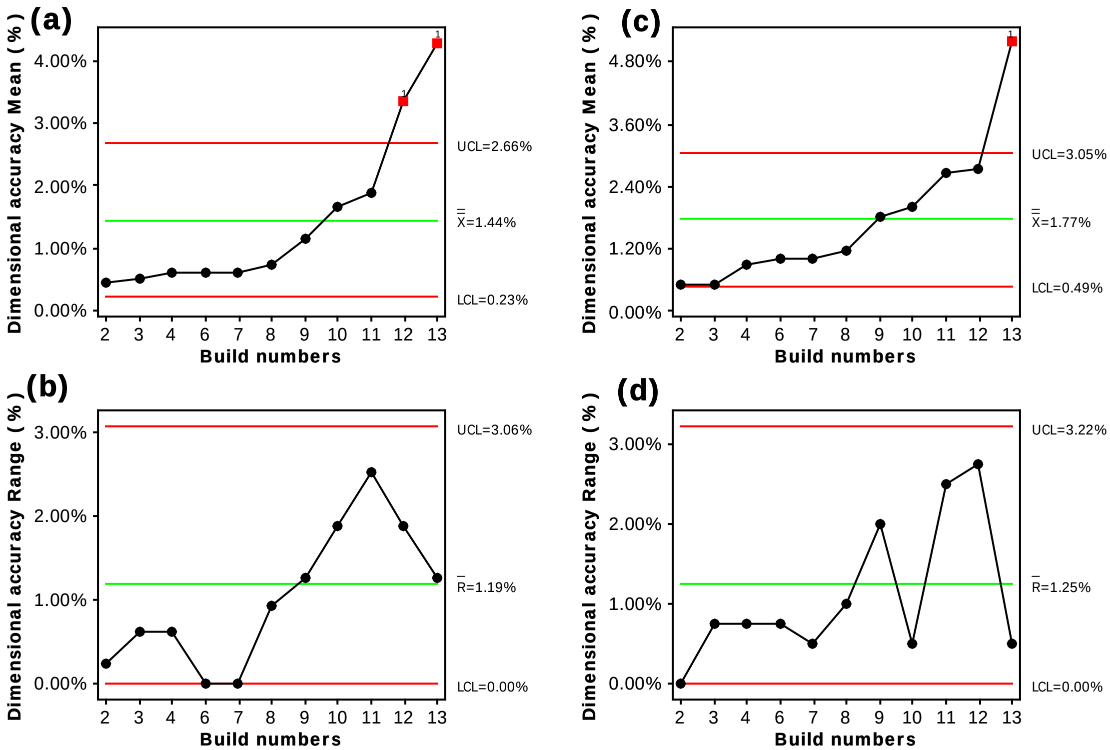

Figure 4 SPC Dimensional accuracies Mean and range charts for Benchmark 1 (a), (b) and for Benchmark 2 (c), (d)

4.4 SPC charts for density

Figure 5 shows the SPC chart for densities of benchmark 1 and benchmark 2 specimens made in multiple builds.

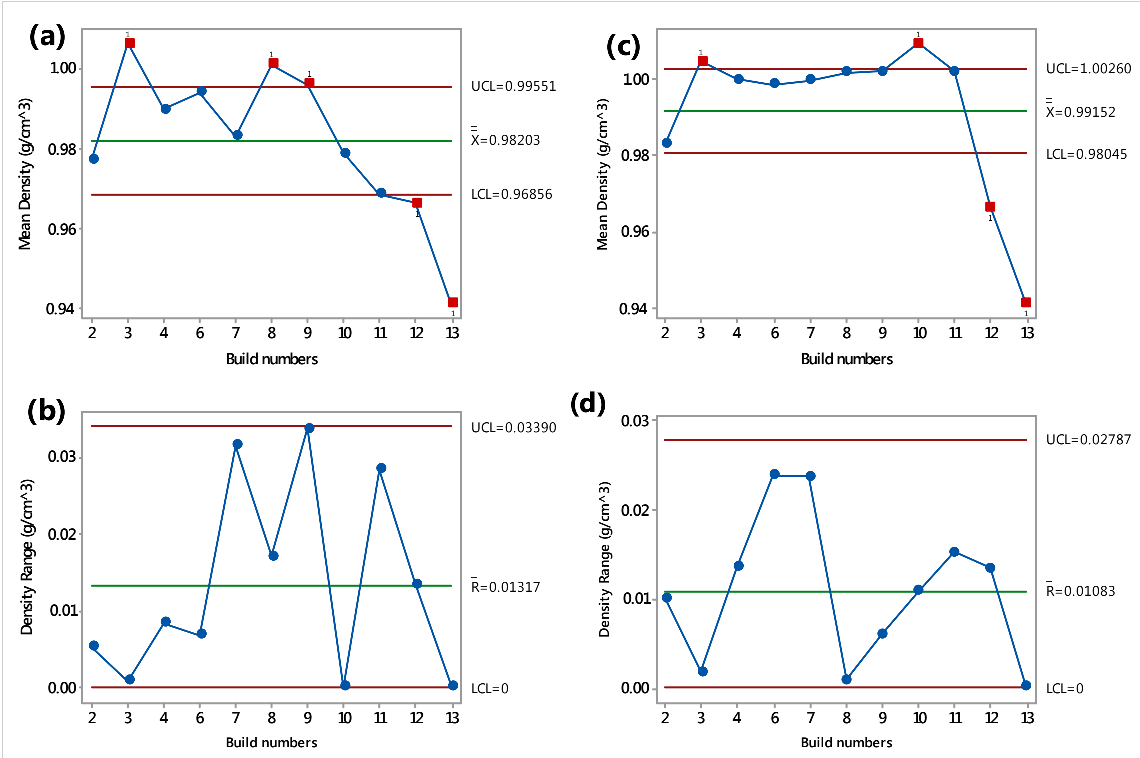

Figure 5 SPC Density (flexural specimens) Mean and range charts for Benchmark 1 (a), (b) and for Benchmark 2 (c), (d)

5. Discussion

Table 2 below summarises the results from the process control charts, where the data from Figures 2, 3, 4 and 5 has been represented as green for points within the control limits, orange for points outwith the control limits but not considered significant, and red for points outwith the control limit and considered significant. Points outwith the control limits but not considered significant relate to measurements of flexural modulus or impact strength where the recorded values exceeded the upper control limit – parts having marginally better mechanical properties than average is not considered a significant concern.

Table 2 Summary of Control Chart States from Build to Build. Green: within control limits; amber: outwith control limits but not significant; red: outwith control limits and significant. BM1: benchmark 1; BM2; benchmark 2.

	Build Number										
Chart Type	2	3	4	6	7	8	9	10	11	12	13
BM1 Flexural Modulus $\bar{x}$											
BM1 Flexural Modulus R											
BM2 Flexural Modulus $\bar{x}$											
BM2 Flexural Modulus R											
BM1 Impact Strength $\bar{x}$											
BM1 Impact Strength R											
BM2 Impact Strength $\bar{x}$											
BM2 Impact Strength R											
BM1 Dimensional Accuracy $\bar{x}$											
BM1 Dimensional accuracy R											
BM2 Dimensional accuracy $\bar{x}$											
BM2 Dimensional accuracy R											
BM1 Density $\bar{x}$											
BM1 Density R											
BM2 Density $\bar{x}$											
BM2 Density R											

On the basis of Table 2 three main observations can be made:-

- For the relatively small number of measurements used in this study, mean charts were more sensitive than range charts.
- The values obtained across the mean control charts for all of the variables from builds 12 and 13 were mostly outwith the control limits, whereas for other builds the values

were mostly either within the control limits, or outwith the control limits but not considered significant.

- The information obtained from benchmark 1 and benchmark 2 was mostly very similar, with the major exception being in the flexural modulus mean charts.

The consistency shown between the mean control chart states suggests that not all of the measures would be required in order to monitor the quality of output, and we have previously investigated the correlation between these measures [24]. For this batch of powder on this machine it would seem that 11 good quality builds have been achieved, but beyond that point the powder has deteriorated to the point where a significant drop-off in quality can be observed.

6. Conclusion

On the basis of table 2 we conclude that, even with relatively small amounts of data, SPC charts can be successfully applied to polymer SLS. In this study mean control charts were more sensitive and of more value in identifying a deterioration in quality than range control charts, with flexural modulus, impact strength, density and dimensional accuracy all fairly well correlated in terms of the information provided in terms of measuring the quality of output from a build.

References

1. Reeves, P. *Additive Manufacturing–A supply chain wide response to economic uncertainty and environmental sustainability*. in *International Conference on Industrial Tools and Material Processing Technologies*. 2009. Ljubljana,Slovenia.
2. Yan, X. and P. Gu, *A review of rapid prototyping technologies and systems.* Computer-Aided Design, 1996. **28**(4): p. 307-318.
3. De Crescenzio, F., et al., *Design and manufacturing of ear prosthesis by means of rapid prototyping technology.* Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 2011. **225**(3): p. 296-302.
4. Heckmann, S.M., et al., *Overdenture attachment selection and the loading of implant and denture-bearing area. Part 1: In vivo verification of stereolithographic model.* Clinical Oral Implants Research, 2001. **12**(6): p. 617-623.
5. Winder, J. and R. Bibb, *Medical Rapid Prototyping Technologies: State of the Art and Current Limitations for Application in Oral and Maxillofacial Surgery*. Journal of Oral and Maxillofacial Surgery, 2005. **63**(7): p. 1006-1015.
6. Hopkinson, N., R.J.M. Hague, and P.M. Dickens, *Rapid manufacturing: an industrial revolution for a digital age*2006: Wiley Online Library.
7. Jacobs, P.F., *Rapid prototyping and manufacturing: Fundamentals of stereolithography*. McGraw – Hill, New York, 1996.
8. Stephen, A.O., K.W. Dalgarno, and J. Munguia, *Development of a quality system for polymer based-selective laser sintering process* in *Proceedings of Solid Free Form Symposium*2013: University of Texas in Austin, Texas, USA. p. 66-75.
9. Beal, V.E., et al., *Statistical evaluation of laser energy density effect on mechanical properties of polyamide parts manufactured by selective laser sintering.* Journal of Applied Polymer Science, 2009. **113**(5): p. 2910-2919.

10. Caulfield, B., P.E. McHugh, and S. Lohfeld, *Dependence of mechanical properties of polyamide components on build parameters in the SLS process.* Journal of Materials Processing Technology, 2007. **182**(1-3): p. 477-488.
11. Ho, H.C.H., W.L. Cheung, and I. Gibson, *Morphology and properties of selective laser sintered bisphenol a polycarbonate.* Industrial and Engineering Chemistry Research, 2003. **42**(9): p. 1850-1862.
12. Chua, C.K., K.F. Leong, and C.S. Lim, *Rapid prototyping: principles and applications*2010, Singapore: World Scientific Pub Co Inc.
13. Choi, J.Y., et al., *Analysis of errors in medical rapid prototyping models.* International Journal of Oral and Maxillofacial Surgery, 2002. **31**(1): p. 23-32.
14. Berry, E., et al., *Preliminary experience with medical applications of rapid prototyping by selective laser sintering. Med. Eng. Phys.* 1997. **19**: p. 90-96.
15. Gornet, T.J., et al. *Characterization of selective laser sintering materials to determine process stability*. in *Solid Freeform Fabrication Symposium,* . August,2002. University of Texas in Austin, USA.
16. Berumen, S., et al., *Quality control of laser- and powder bed-based Additive Manufacturing (AM) technologies.* Physics Procedia, 2010. **5, Part B**(0): p. 617-622.
17. Krauss, H., C. Eschey, and M.F. Zaeh. *Thermography for Monitoring the Selective Laser Melting Process*. in *Solid Freeform Fabrication Symposium*. 2012. Austin, Texas.
18. Craeghs, T., et al. *Online quality control of selective laser melting*. in *Solid Freeform Fabrication: Proceedings*. 2011. Austin, Texas.
19. Hanna, S.M. *Application of Statistical Process Control (SPC) in the manufacturing of medical accelerators*. in *Particle Accelerator Conference, 2003. PAC 2003. Proceedings of the*. 2003. IEEE.
20. Oakland, J.S., *Total quality management : the route to improving performance*. 2nd ed1993, Oxford ; Boston: Butterworth-Heinemann. x, 463.
21. Wadsworth, H.M., *Handbook of statistical methods for engineers and scientists*. Vol. 14. 1990: McGraw-Hill New York etc.
22. Cook, G.E., et al., *Statistical process control application to weld process.* Industry Applications, IEEE Transactions on, 1997. **33**(2): p. 454-463.
23. MacGregor, J.F. and T. Kourti, *Statistical process control of multivariate processes.* Control Engineering Practice, 1995. **3**(3): p. 403-414.
24. Akande, S.O., et al., *Assessment of tests for use in process and quality control systems for selective laser sintering of polyamide powders.* Journal of Materials Processing Technology, 2016. **229**: p. 549-561.
25. Gygi, C., B. Williams, and T. Gustafson, *Six Sigma Workbook For Dummies*2006, Hoboken: John Wiley & Sons Inc. 314.
26. Wetherill, G.B. and D.W. Brown, *Statistical process control : theory and practice*. 1st ed1991, London ; New York: Chapman and Hall. xiv, 400.