DEVELOPMENT OF A QUALITY SYSTEM FOR POLYMER BASED-SELECTIVE LASER SINTERING PROCESS

A. O. Stephen*, K. W Dalgarno*, J. Munguia*
*School of Mechanical and Systems Engineering, Newcastle University, Newcastle, UK

Abstract

The aim of this study is to develop a quality system for selective laser sintering, based on defining a minimum set of tests to qualify a build. MFI, impact and flexural tests were assessed, along with density, dimensional measurements and SEM. A benchmark part was designed for manufacture to track changes in key parameters from build to build, and tests on this validated against ISO standards. It is concluded that a combination of measures of flexural modulus, density and impact strength can be used for process monitoring and to infer the quality of a build in SLS process.

1. Introduction

The two methods of manufacturing that have dominated to date are subtractive (machining) or formative processes such as casting, injection moulding and forging. However, more recently the growth in three dimensional computer aided design software has enabled the production of product 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]. This new set of manufacturing methods is called additive manufacturing (AM). The building methods for additive manufacturing includes 3-D printing (3 DP), fused deposition modelling (FDM), laminated object manufacturing (LOM), selective laser sintering (SLS), selective laser melting (SLM) and stereolithography (SLA) [3-5]. The various processes are cost effective methods for the production of custom made parts based on customer requirements and are also good for low volumes with potential for medium and high volume production [6, 7].

Parts made by these processes initially were for prototypes, concept verifications and analysis but technical improvements, better process control and the ability to use more materials resulted in a shift to rapid tooling and more recently to rapid manufacturing [8, 9].

The SLS process uses a laser that sinters selectively a thin layer of powder spread over a platform. A computer directs a laser scanning mirrors over the powder layer, sintering and attaching a new layer of the part [4]. Each time a layer is finished, the platform is lowered and a new layer of powder is spread over the previously built layer. This process is repeated sequentially until the part is completed and the sintered product is then separated from un-sintered powder after the cooling down stage.

The common practice in Laser Sintering-based systems involves the blending of virgin powder with used powder to reduce cost and increase material utilisation. However part properties have been shown to later reduce as a result of repeated exposure to heat [10].This results in different chemical and structural properties and consequently lower physical and mechanical properties of the final part. A powder life study was carried out by Choren et al. [11] by increasing laser power relative to powder age, and it was observe that although increase in laser power increases most mechanical properties but higher powers and older powders chemically degrade the powder.

Gornet et al. [10] used an extrusion plastomer (a device that is normally used in plastic industries to measure the quality of resins and grade polymer) to assess powder properties with repeated use. It was observed that after several builds the melt flow rate (MFR) of polymer decreased with number of builds, an indication that the polymer is degrading. Low melt flow index was also attributed to improvement of elongation at break. Melt - flow rate (MFR) or melt volume - flow rate (MVR) is the rate of extrusion of a thermoplastic or resin through an orifice of standard dimensions under prescribed temperature and pressure [12].

Various researchers have carried out work in improving the quality of fabricated part in addition to the aforementioned. Schmid and Levy [13] presented a generic model for the development of quality management system for additive manufacturing with selective laser sintering process. 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. [14] for metal parts. Krauss et al.[15] 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 [16]. However no correlation was made between the evolved material properties and the process parameters.

The various research efforts point to the fact that a quality management system is very important for the future of additive manufacturing as the standardization activities are still at infancy level [13]. Overall the need of ensuring that AM processes deliver reliable and predictable properties cannot be overemphasised. Currently, the inability to guarantee material properties is holding back the adoption of AM technologies as industry does not have the confidence that manufactured parts will have the required mechanical properties for specific needs. This paper will therefore look at basic mechanical property variation with builds with the aim of developing a quality system for polymer based SLS systems.

2. Testing Rationale

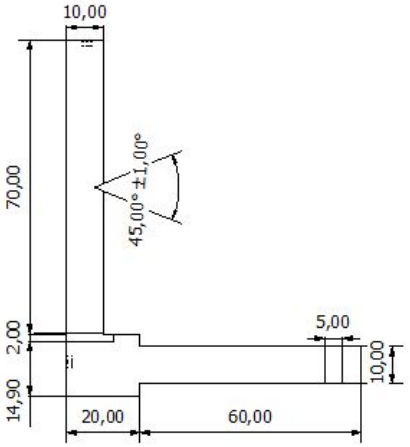
2.1. Requirements for a QA test

Quality assurance (QA) is defined as various organized procedures that ensure quality requirements for a product are satisfied. However, since it involves resources there is need of ensuring that the QA test will be simple, small, reliable, cheap and capable of being carried out quickly.

2.2. Evaluation of Possible QA Tests

A benchmark part was designed and fabricated to capture the key quality characteristics, after a review of various design. One benchmark sample design patterned after ISO designs for bending modulus and impact strength is involved in this study.

Figure 1 shows the design for Benchmark part with dimensions all in millimetres.



Benchmark (thickness of 4 mm)

Figure 1 the geometrical design for Benchmark part

3. Experimental procedures

Nylon SLS specimens were made by Peacocks Medical Group, Newcastle in Duraform PA 12 material, using a 3DSystems sProSD SLS machine, and with the processing conditions shown in Table 1.

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

Equipment	3D Systems sPro60SD
Laser power	12 W
Outline laser power	6 W
Fill scan spacing	0.15 mm
Laser scan strategy	Cross Fill Scanning
Layer thickness	0.1 mm
Scan speed	5 m/s

3.1. Test specimens

Flexural specimens (Figure 2) were made in accordance with BS EN ISO 178:2010 [17] with the tests conducted using an Instron 4505 electromechanical system at a cross speed of 2 mm/min and were oriented in X, Y and Z directions as shown in Figure 2. Fifteen specimens with each five oriented in X, Y and Z directions were made for the flexural properties determination.

Izod notch impact test specimens (Figure 3) were made also according to BS EN ISO 180:2001 method A [18]. Tests were then carried out using a pendulum impact tester with pendulum capacity of 22 J. Fifteen specimens were made in a pack of five and oriented in X, Y and Z directions as shown in Figure 3 to reduce variability in thermal history due to locations in the build chamber by beams of thin section, which can be easily separated from each specimen after build. The build setup is also shown in Figure 2.

(a) (b)

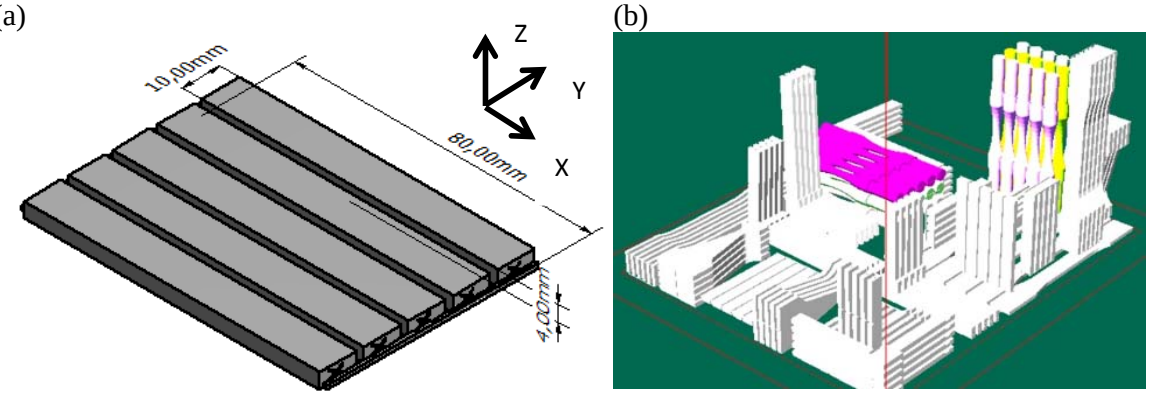
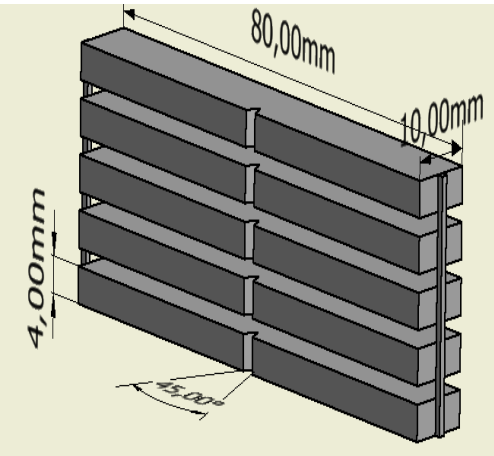


Figure 2 (a) Five flexural specimen parts with dimensions (b) build setup with orientations



ISO sample size

Figure 3 Five impact specimen parts with dimensions

3.2. Test Procedures for Benchmark

Samples were clamped in a jig (fabricated using Rapid manufacturing (SLS) with EOS PA2200 material). The testing procedures involved the placing of the benchmark sample in bottom block with a groove that fit the geometry of the sample and then placing of the top block on the sample such that the benchmark sample is sandwiched between the top and the bottom block of the jig. They are then clamped together in position with the aid of aluminium plate, two 100 mm bolts and wing nuts. Digital dial gauge is clamped vertically to sliding horizontal brackets whose position can be adjusted based on the length of the beam. The loads of 100g and 150g were hanged sequentially on the beam and readings of deflection for each load were then taken using Mitutoyo digital indicator. The data obtained was then used to compute the modulus for the beam.

Figure 4 Positioning of the specimen during bending

3.3. Determination of density of specimens

Approximate density of specimens was computed from measured volume obtained by measuring the dimensions (length, width and thickness) of the benchmark specimens using Mitutoyo digital calliper, which was then used for calculating the volume. The mass was measured with a precision balance (KERN PFB 200-3).

4. Experimental results

4.1. Densities, flexural modulus and impact strengths of benchmark specimens with number of builds

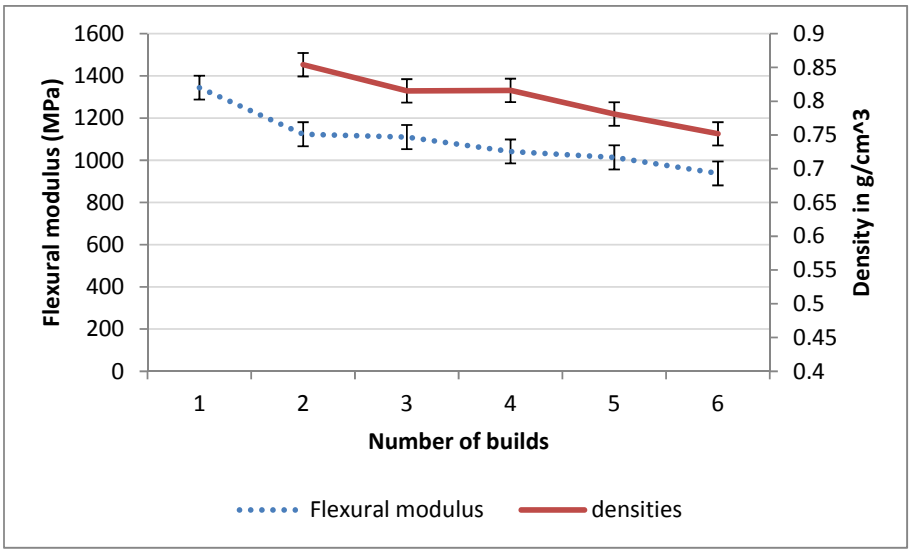


Figure 5 Variations of modulus and densities of Benchmark part with build

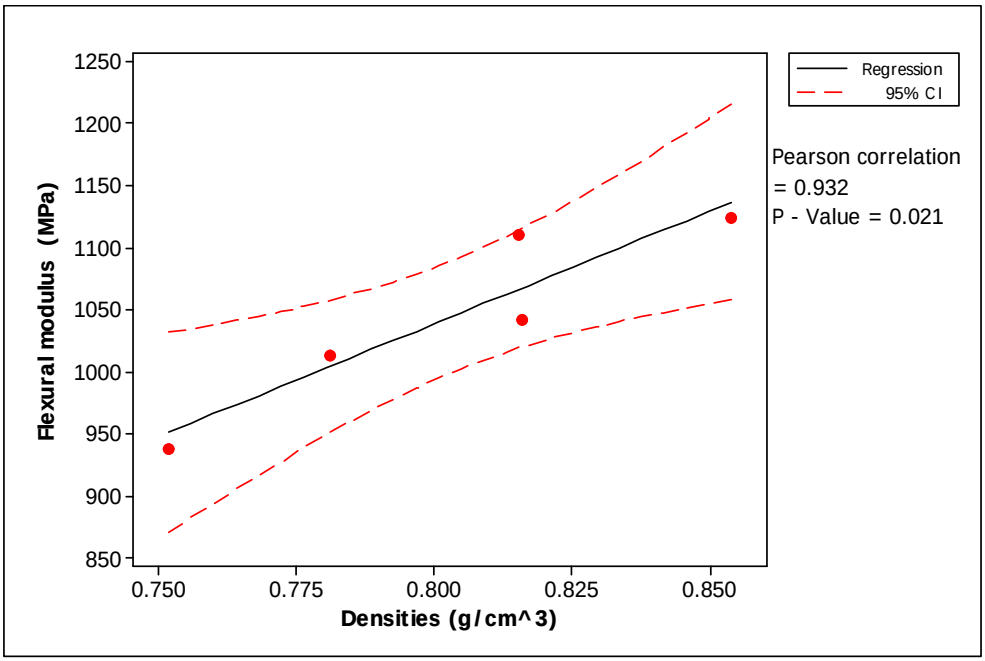


Figure 6 Correlation between Flexural modulus and densities of Benchmark part specimens

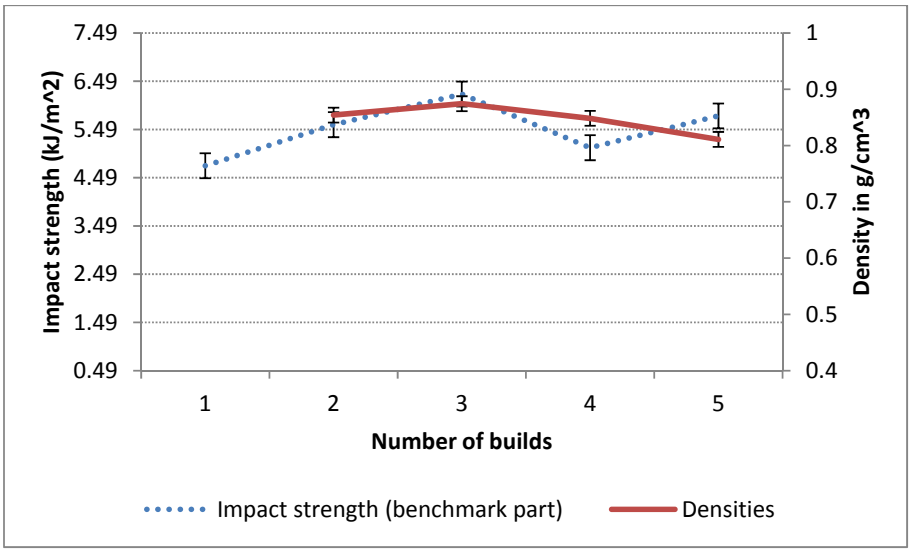


Figure 7 Variations of impact strength and densities of Benchmark part with builds

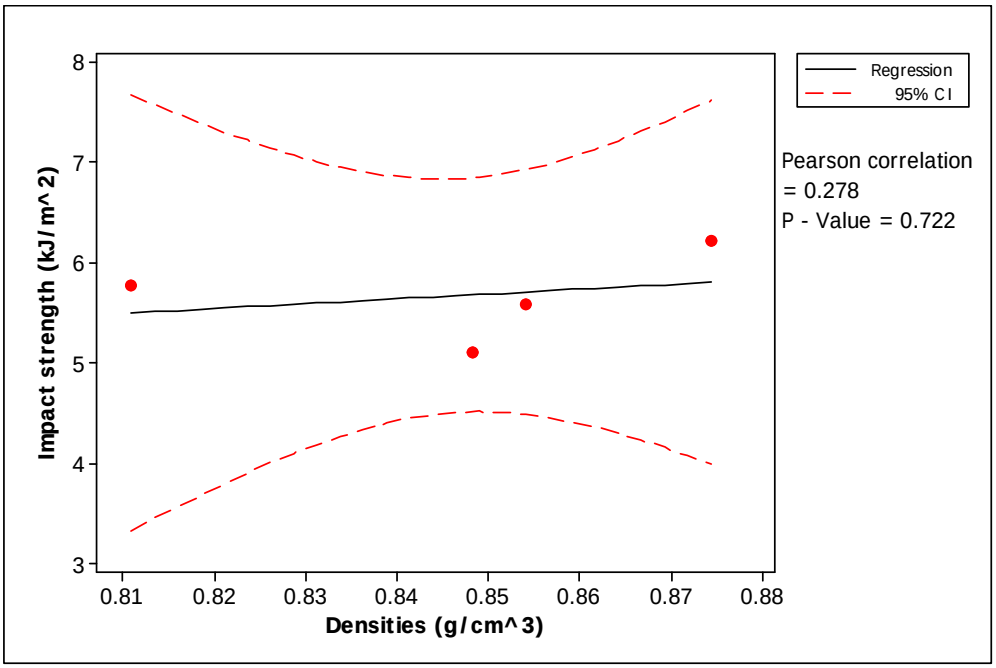


Figure 8 Correlation between impact strength and densities of Benchmark part

4.2. Impact strengths, flexural modulus of ISO and benchmark samples

Correlation between benchmark samples and ISO samples in the same build is shown in Figure 9.

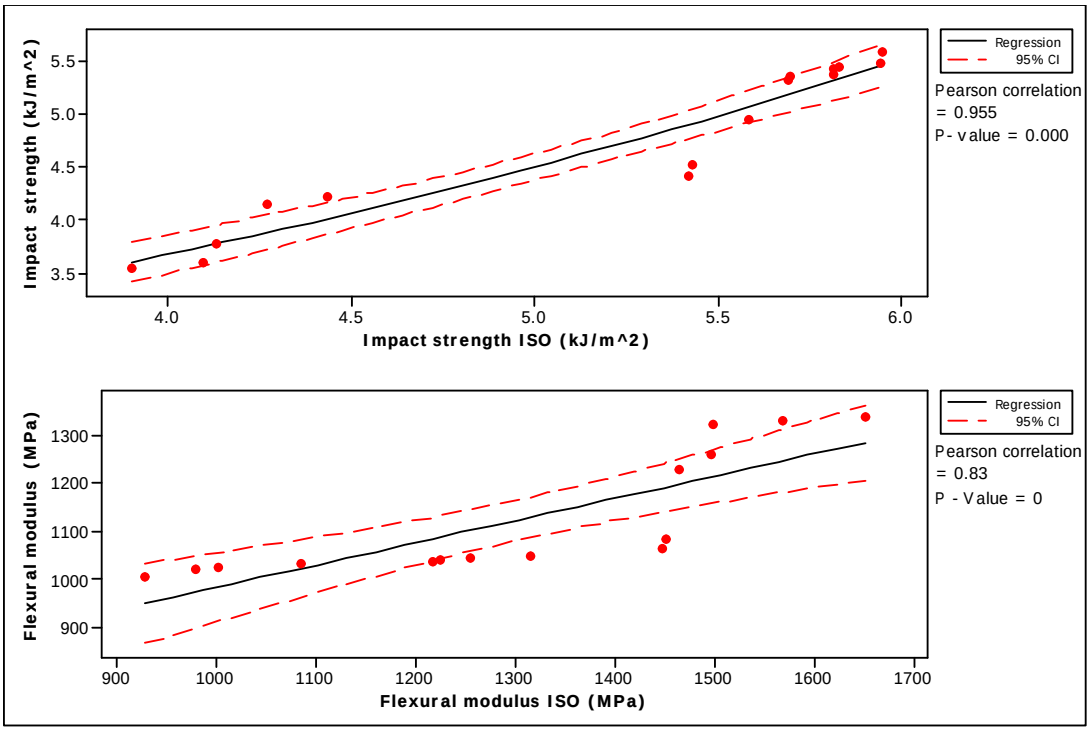


Figure 9 Correlation between ISO and benchmark impact and bending samples in a build

5. Discussion

5.1. Correlation of densities, flexural modulus and impact strengths of benchmark specimens with number of builds

The density of a sintered part has been shown to affect the mechanical properties of parts [19]. Usually higher density results into superior strength due to reduction in porosities or voids that can serve as points of stress concentration. Also, there is greater possibility of crack initiation and failure for lower density sintered part due to presence of more un-sintered powder particles in the part [20, 21].

From Figure 5 it can be observed that there is direct relationship between the density and the bending modulus for the benchmark samples. The correlation coefficient (Figure **6**) is 0.932 with p – value of 0.021 which is less than the alpha level of 0.05 (above which the model can be said not to fit well to the data) [22]. The variation in densities may be due to a number of reasons some of which include: low powder bed temperature, energy density [19, 23], and interactions between them.

Similarly, impact strengths (Figure 7) vary with densities and build with the exception of build five for the benchmark sample. However, correlation between impact strengths and densities (Figure 8) was not statistically significant (p –value = 0.722) which may be due to surface flaws. Furthermore, molecular orientation and weight are also known to influence strength of polymer [24]. This may have been the reason for increase in impact strength in build five (with low MFI) in addition to increase in density. Also molecular weights has been suggested to be responsible for increase in elongation at break for laser sintered part [10, 25]. However, there is optimum range of molecular weight for laser sintering polymers as pointed out by Goodridge et al.[21] and Kruth et al.[26] beyond which the material properties will deteriorate. Thus the density of sintered parts, molecular weight and their interactions could be say to influence the mechanical properties of laser sintered part.

5.2. Correlations of ISO impact strength and flexural modulus with that of Benchmark samples

From Figure 9 the correlation coefficient between Benchmark and ISO impact samples is 0.96 with p –value of 0. Similarly, the correlation coefficient between the flexural modulus of Benchmark and ISO samples is 0.83 with the p – value of 0. Thus, correlation exists between the benchmark tests and ISO tests.

6. Conclusion

Flexural modulus and impact strength were found to vary with density and the number of builds with a strong positive correlation observed between benchmark flexural modulus and density.

Correlation between Benchmark specimens and ISO specimens in the same build was carried out with positive correlation observed between them.

In this study also, benchmark parts have been designed, manufactured and validated against that of ISO designed test specimens. The benchmark samples have demonstrated ability to capture the key quality characteristics of strength, stiffness and dimensional accuracy (the minimum resolution that the benchmark can capture is 1.2 mm) with number of builds. This therefore, opens a prospect for its usage in process monitoring and control. Further work is on-going in the implementation of the quality system with another material

and in partnership with an industrial partner. Within a quality system, one benchmark specimen is recommended to be added to each build and placed about the same region in a build volume. The aforementioned quality characteristics can then be used independently or jointly depending on the desired monitor/control level that is required by the user and the available test resources. The data could also be used in statistical process control. Therefore, on the basis of the data from this study a proposed novel and cost effective quality system will therefore consist of qualification of input materials by the use of MFR and qualification of a build by the use of benchmark samples (density, stiffness and dimensional accuracy). The result will be very useful in ensuring properties consistencies from build to build as SLS transits from rapid prototyping to manufacturing of functional part.

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. Wohlers, T. *Past, present, and future of rapid prototyping*. in *First International Conference on Advanced Research in Virtual and Rapid Prototyping* 2003. Portugal.
4. Jacobs, P.F., *Rapid prototyping and manufacturing: Fundamentals of stereolithography.* McGraw – Hill, New York, 1996.
5. Bocking, C., et al., *Electrochemical routes for engineering tool production.* GEC Journal of Technology, 1997. **14**(2): p. 66-74.
6. Hague, R., I. Campbell, and P. Dickens, *Implications on design of rapid manufacturing.* Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 2003. **217**(1): p. 25.
7. Anon, *The solid future of rapid prototyping*, in *The Economist Technology Quarterly*2001, Economist Group: USA. p. 47 - 49.
8. Kruth, J.P., et al. *Advances in selective laser sintering*. in *1st Int.Conf. on Advanced Research in Virtual and RapidPrototyping (VRAP2003),*. 2003. Leiria,.
9. Levy, G.N., R. Schindel, and J.P. Kruth, *Rapid manufacturing and rapid tooling with layer manufacturing (LM) technologies, state of the art and future perspectives.* CIRP Annals - Manufacturing Technology, 2003. **52**(2): p. 589-609.
10. 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.
11. Choren, J., et al. *SLS powder life study*. in *Solid Freeform Fabrication Symposium*. 2001. University of Texas at Austin.
12. ASTM D1238-10, *Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion*, 2010, ASTM International, 100 Barr Harbour Drive,Pennnsylvania, USA. p. 15.
13. Schmid, M. and G. Levy, *Quality Management and Estimation of Quality Costs for Additive Manufacturing with SLS.* 2011.
14. 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.
15. Krauss, H., C. Eschey, and M.F. Zaeh. *Thermography for Monitoring the Selective Laser Melting Process*. in *Solid Freeform Fabrication Symposium*. 2012. Austin, Texas.
16. Craeghs, T., et al. *Online quality control of selective laser melting*. in *Solid Freeform Fabrication: Proceedings*. 2011. Austin, Texas.
17. BS EN ISO 178:2010, *Plastics - Determination of flexural properties(ISO 178:2010)*, 2010, European Standards, International Organization for Standardization: Switzerland.

18. BS EN ISO 180:2001, *Plastics - Determination of Izod impact strength*, 2001, European Standards, International Organization for Standardization: Switzerland. p. 16.
19. Tontowi, A.E. and T.H.C. Childs, *Density prediction of crystalline polymer sintered parts at various powder bed temperatures.* Rapid prototyping journal, 2001. **7**(3): p. 180-184.
20. Van Hooreweder, B., et al., *Microstructural characterization of SLS-PA12 specimens under dynamic tension/compression excitation.* Polymer testing, 2010. **29**(3): p. 319-326.
21. Goodridge, R.D., C.J. Tuck, and R.J.M. Hague, *Laser sintering of polyamides and other polymers.* Progress in Materials Science, 2012. **57**(2): p. 229-267.
22. Ryan, B.F., B.L. Joiner, and J.D. Cryer, *Minitab handbook : updated for release 14*. 5th ed2005, Belmont, CA: Thomson/Brooks/Cole. xv, 505.
23. Ho, H.C.H., I. Gibson, and W.L. Cheung, *Effects of energy density on morphology and properties of selective laser sintered polycarbonate.* Journal of Materials Processing Technology, 1999. **89**: p. 204-210.
24. Cai, J., et al., *Effects of molecular weight on poly(ω-pentadecalactone) mechanical and thermal properties.* Polymer, 2010. **51**(5): p. 1088-1099.
25. Zarringhalam, H., et al., *Effects of processing on microstructure and properties of SLS Nylon 12.* Materials Science and Engineering: A, 2006. **435**: p. 172-180.
26. Kruth, J.P., et al., *Consolidation phenomena in laser and powder-bed based layered manufacturing.* CIRP Annals-Manufacturing Technology, 2007. **56**(2): p. 730-759.