Production of functional parts using SLM – Opportunities and limitations

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ABSTRACT: Different Additive Manufacturing Technologies have already a certain stage of maturity, allowing a wide range of applications. In the field of metal processing, Selective Laser Melting (SLM) is already growingly used in different applications such as tooling (Conformal Cooling) and for the production of small series of smaller sized complex functional parts in metal. However, the technology still sets limitations for the use in applications and sectors where a high material integrity is required, such as medical implants or parts for aerospace etc. Nevertheless, the overall options using this technology e.g. for lightweight applications for the automotive and aerospace industry are recognized. Exemplary, the development of specially designed brackets for the ETHZ-formula student racing car and their production using SLM are presented. The process specific limitations regarding the material integrity are discussed, pointing out the needs for a further development of the technology in order to allow the future use of SLM in high performance technological applications and sectors.

1 INTRODUCTION

The Selective Laser Melting (SLM) technology is a freefrom fabrication process that allows the production of parts in diverse metallic materials such as diverse stainless steel types, hot-work steel, Titanium, Aluminum, Nickel-based alloys, Cobalt-Chromium and others (Lohmeier 2005, Abe et al. 2003, Santos et al. 2004, Shellabear 2008, Uckelmann 2006, Mumtaz et al. 2008, Averyanova & Bertrand 2010, Childs et al. 2005, Gu & Shen 2008, Lopez et al. 2008). It is a layer-wise process where a high energy laser beam scans on a powder bed successively the cross-sections of a sliced CAD data file of the required part. This leads to the consolidation of the metallic powder particles in the scanned area, resulting in a nearly fully dense layer of the part being built. Successive lowering the build platform, generating the next powder layer and scanning the cross-sections leads to the final physical part.

The properties of additive manufactured materials are already widely analyzed by many researchers: Density (Spierings & Levy 2009a), microstructure (Klingbeil et al. 2004, Kruth et al. 2004, Simchi 2006) and the static mechanical performance (Sehrt & Witt 2009, Spierings et al. 2011, Yasa et al. 2010) are well studied, pointing out that the static mechanical properties are typically in the range of wrought conventional materials, although a specific anisotropy of several percent can be observed. The dynamic mechanical properties however are so far only partially analyzed for some specific materials and AM processes (Sehrt & Witt 2010, Spierings et al. submitted, Christensen et al. 2007). An analysis of stainless steel 316L and 15-5PH shows that the fatigue limit typically is lower compared to conventional materials, even for polished samples (Starr & Spierings 2010). Interestingly, the part's surface quality plays only a minor role within the dynamic lifetime range (Spierings et al. submitted). As a result, if the dynamic strength fits to the application- and design-specific requirements, the way for a usage of SLM for diverse industrial applications would be open, allowing a real Additive Manufacturing (AM) instead of simple Rapid Prototyping.

However, besides the description of the material microstructure and some mechanical properties, the today's knowledge about the correlation between the microstructure of SLM materials and corresponding properties are still poorly analyzed. In this respect, only little work has been put in the analysis of e.g. the fracture toughness, the dynamic impact strength (Yasa et al. 2010) or further parameters where the microstructural situation of SLM materials plays an important role.

This is at least one reason hindering the SLM technology evolving in industry, especially in high-technological areas: Companies are careful in cases of high technological requirements on the material side and as they typically have limited knowledge and access to the material specific property databases. This holds especially for the subsuppliers. A further reason might be the production costs, which can be high especially for high-volume parts due to a limited process-productivity and auxiliary required support structures that have to be removed manually. As a consequence, SLM is still mostly used for the production of prototypes although in many cases the technology would fulfill the application-specific requirements.

The fact that the industry requires metal AM-products is supported by Munguía (Munguia 2008) who performed a survey in the industry about their real needs. The results show that about 37% of all answers required diverse metal materials. In this respect, SLM has already been used for the production of parts for diverse applications: The production of tools containing complex cooling channels (Conformal Cooling) is already state of the art and allows the reduction of cycle time and the improvement of the part quality in plastic injection molding (Gravet 2008, Herzog 2008, Spierings & Levy 2009b, Villalon 2005) and the additive production of dental cups and bridges in Cobalt-Chromium is already performed on a daily basis by several industrial service providers. Further fields of application are in medical engineering for the production of instruments and implants and there is a wide potential for lightweight structures using internal grid structures (Rehme & C 2006) with potential application in the automotive and aerospace industry. No other process allows the production of structures with a comparable high complexity (Figure 1).

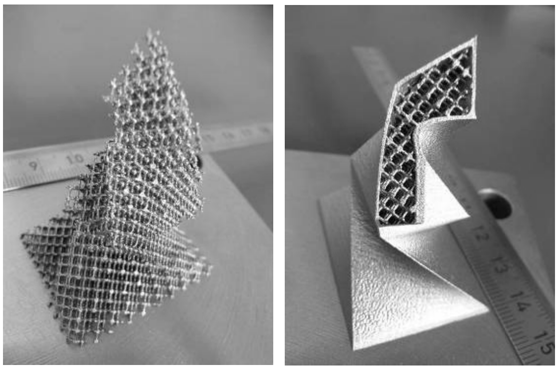


Figure 1: Example of a grid-structure without (left) and with (right) a shell; produced by SLM at inspire-irpd

In order to motivate industry to use additive manufacturing technologies, in this case SLM, the current publication shows a case study about the development, results and potential of the use of SLM by producing brackets for the Formula Student Car 2010 and 2011 of the team of ETH Zurich, first place winner in Silverstone 2010. On this basis opportunities and limitations of SLM are discussed pointing out the need for a specific further development of the technology.

2 CASE STUDY

2.1 *About Formula Student*

(Formula_Student_webpage 2011): *"Formula Student (FS) is Europe's most established educational motorsport competition, run by the Institution of Mechanical Engineers. Backed by industry and high profile engineers such as (...) Ross Brawn, the competition aims to inspire and develop enterprising and innovative young engineers. Universities from across the globe are challenged to design and build a single-seat racing car in order to compete in static and dynamic events, which demonstrate their understanding and test the performance of the vehicle"*

2.2 *Brackets of the FS-car of ETH Zurich*

The brackets are the key elements of the connection between suspension and chassis. All the static and dynamic loads occurring during a race are lead through the wishbones to the brackets and finally into the monocoque itself. As one can see easily, high dynamic forces are applied on these elements. In total, eight different types of bracket geometries, each in a right and a left version, are needed to attach the beams of the front- and rear suspension to the frame. Additionally, brackets for the attachment of the spring-damper elements are necessary.

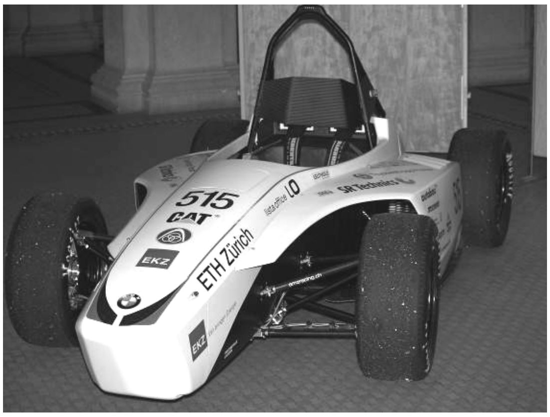


Figure 2: AMZ Formula Student Car 2010 & 2011

The aim of the case study was to use SLM as an innovative method for the production of the complex brackets, to investigate the usability of additive manufactured parts in under real loadings and to identify the potential and limitations of SLM regarding its use in an industrial environment.

3 MATERIALS AND METHODS

3.1 *Production of the brackets with SLM*

The brackets were produced using a Concept Laser M2 machine, which is equipped with an Nd-YAG laser and a fiber is used for beam delivery The reported M^2 of the laser source is 1.02. The maximum laser power at the building platform is about 190W. The scan strategy used to produce the brackets is a chessboard-like structure, where 5x5 mm^2-squares are scanned. More details are described in (Spierings & Levy 2009a, Badrosamay et al. 2009).

The brackets were produced in 30µm layers using the maximal laser power and a scan-speed of 1050 mm/s. The orientation of the brackets during the build process, affecting the mechanical properties due to the anisotropy, was selected according to the requirement for a stable and easy process. As typical in industry orientation dependent properties of the material were not taken into account.

3.2 Material

Stainless steel 316L was selected as a suitable material for the brackets. This material is a well-known material for SLM with good mechanical properties (Table 1). The powder granulation plays a significant role regarding the mechanical properties and the processing characteristics. Details about the powder are described in (Spierings & Levy 2009a). The material is characterized by both static (Table 1) and dynamic (Figure 3) mechanical measurements (Spierings et al. submitted). It can be seen that for dynamic strength the measured (---) stress amplitude values for R = 0.1 (surface "as built") are higher compared to literature values and are even in the range of R = -1 for standard materials (GRANTA-software 2011).

Table 1: Static mechanical properties of SLM produced and conventional stainless steel 316L

Material 316L	Yield strength	Ultimate strength UTS	Elongation at break
	(MPa)	(MPa)	(%)
SLM[*]	640	760	30
Handbook[**]	170 - 310	480 – 620	30 – 50

[*] (Spierings et al. 2010, Spierings et al. 2011); [**] (GRANTA-software 2011)

The observed anisotropy in the UTS between the vertical and the horizontal build orientation is typically between 5% and 15% (Spierings & Levy 2009a, Sehrt & Witt 2009), depending on material type and powder granulation.

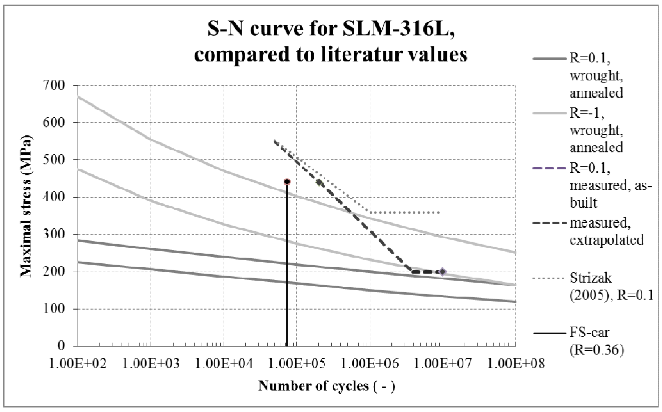


Figure 3: Comparison of SLM-316L to literature values. Wrought, annealed values by (GRANTA-software 2011)

3.3 *Load case for the most critical bracket*

All bracket types were analyzed regarding their acting forces and mechanical stresses using a FEM calculation with ANSYS. Exemplary, the static load case for most critical bracket ("front suspension", Figure 4) is presented in Table 2. Breaking and cornering (inside, outside) lead to dynamic loads on the brackets. For 1000 laps (around 1000 km) and 25 curves per lap, a total of 75,000 cycles occur.

Table 2: External loads on bracket Nr. xx.

Load case	F_x	F_Y	F_Z
	(N)	(N)	(N)
Static load	-698	-1338	473
Cornering outside	-560	-1115	380
Acceleration	413	822	-280
Brake	1077	2143	-730

There are no torques acting on the brackets.

4 RESULTS

4.1 *Brackets 2010*

The brackets were directly assembled to the chassis of the car (different composite structures) without any additional supporting structures (Figure 4).

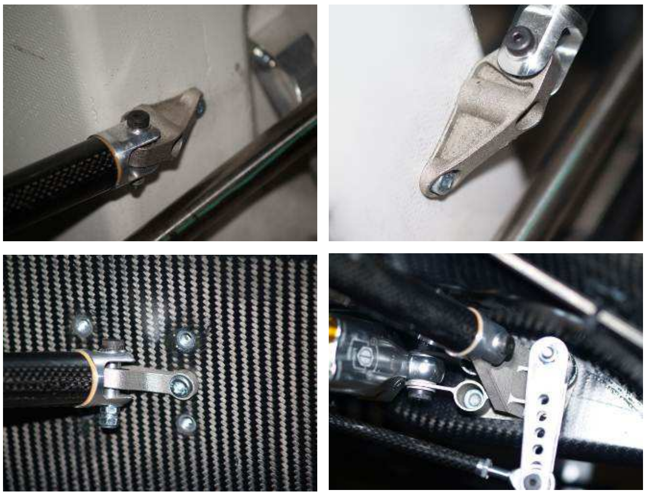
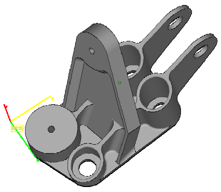
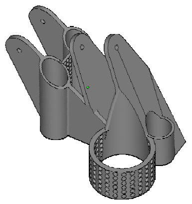
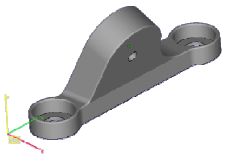
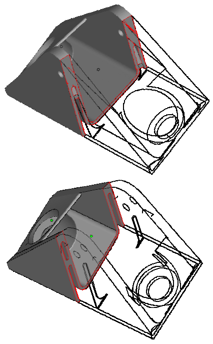
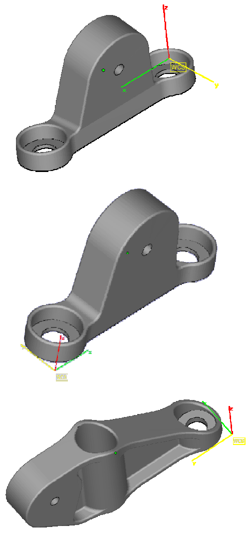
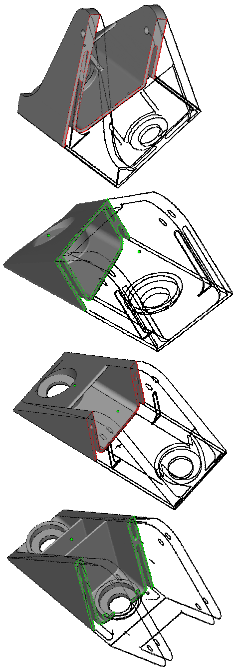


Figure 4: Examples of mounted brackets (Version 2010). Upper left, right: rear suspension; lower right: spring-damper, front suspension and anti-roll bar; lower left: front suspension;

4.2 *Bracket design and FEM analysis*

The FEM analysis for the front suspension-bracket showed that the part was highly over dimensioned. However, due to the lack of experiences, fatigue and fracture toughness data of this material, the brackets were successfully produced and mounted on the car (Figure 4). During one race-year, no problems were reported regarding these brackets. On the basis of the positive results, the overall need for a further reduction of the car's weight and additional fatigue results (Spierings et al. submitted), the brackets for 2011 were re-designed with special emphasis on mass reduction (Table 3).

Table 3: Bracket geometries for FS-car 2010 and 2011

Bracket type	FS-car 2010	FS-car 2011
Front brackets: Spring-damper, front suspension and anti-roll bar left / right		
brackets, left	 2x	
Left and right:		
V_{tot} Front	63.6 cm^3	35.1 cm^3
Rear brackets left (without rear spring-damper)	 2x	
Left and right: V_{tot} Rear	67.1 cm^3	31.4 cm^3

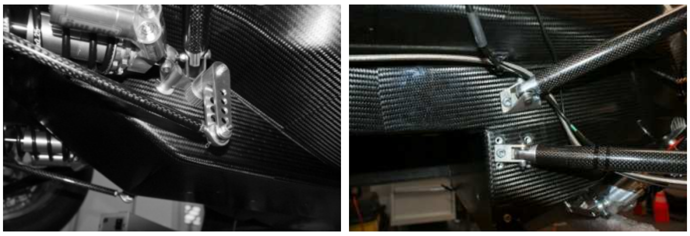
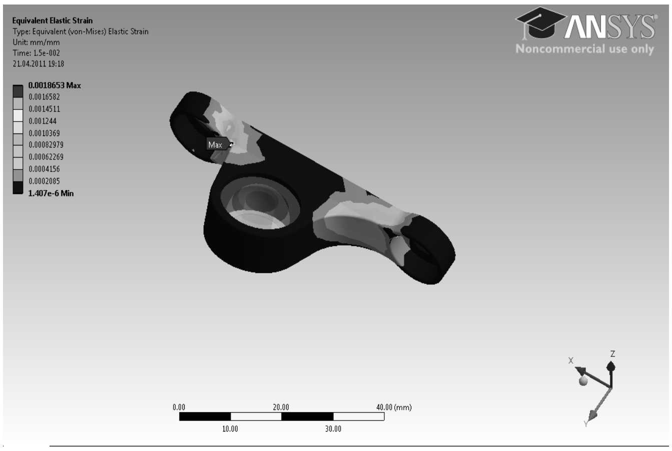


Figure 5: Examples of mounted brackets Version 2011

The FEM analysis showed again that the Von-Mises stresses of most of the part structure were smaller than 100 MPa. In the critical point, the maximum stress was 373 MPa, which is about ½ UTS (Table 1), indicating a high margin of safety. The dynamic evaluation showed a mean stress of 300 MPa (static load) and a stress amplitude of about 140 MPa ($R \approx 0.36$). Although this R-value is somewhat higher compared to measured values, the maximum stress of 440 MPa is acceptable (Figure 3).



Equivalent Elastic Strain
Type: Equivalent (von-Mises) Elastic Strain
Unit: mm/mm
Time: 1.5e-002
21.04.2011 19:18

Figure 6: FEM analysis of the front suspension bracket : static load case

Although the stiffness and the maximum stresses are similar compared to the ones of last year, the total volume of the brackets is distinctively smaller. The brackets of 2010 have a total volume of 115.3 cm^3 and those of 2011 have a volume of 66.5 cm^3 (Table 3). After mechanical finishing the brackets, a total weight reduction of 34% was achieved.

The bracket redesign 2011 consider AM adequate options in complex geometry and light weight. A further optimization in the style shown in Figure 1 was not considered. This was not performed as the whole chassis of the car 2011 remained the same, defining the positions of the brackets etc. A further improvement of bracket design and weight will be considered in future.

4.3 *Bearing bolts*

The bearing bolts 2010 were made in Aluminum 7075-T6, whereas the 2011 versions were made in steel. Although steel is around 2.8 times heavier than Aluminum, design optimizations finally lead to the same weight. However, the benefit was a significant increase in stiffness.

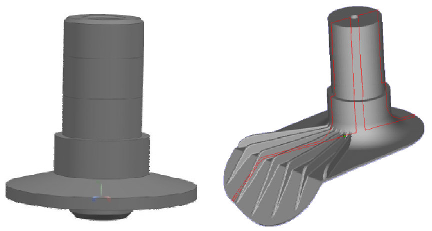


Figure 7: Bearing bolts Version 2010 (left) and 2011 (right)

5 LESSONS LEARNED

5.1 *Challenges for a future use of SLM in industry*

SLM at present is industrially used for the production of either series of small parts (e.g. dental products) or for the production of complex medium sized metal parts. In low quantity such as tools with integrated conformal cooling channels. However, for many industrial applications, typical serial sizes required are in the range of 10 to 100 pieces or more. For such cases, economical limits are dominant. SLM is still an expensive process due to its low productivity, and followed by intensive manual work post-processing operations. Therefore and against the background of real industrial needs (Munguia 2008) there are several aspects that require a further development (Bourell et al. 2009) in order that SLM can find its way to a wider industrial acceptance and well-established production technology. Main emphasis should be put on the following aspects (Figure 8).

a) Material database

- Development of a comprehensive database covering all relevant materials and industrial applications. The database should contain all relevant information needed to successfully dimension structural parts. This requires information about their mechanical properties: anisotropic static and fatigue behavior, impact strength, compression strength, fracture toughness, etc.
  Moreover a description of recommended process and post-process information should be included: influences of different surface finishing operations (Spierings et al. submitted) and other post processes like HIP etc.
- Development of suitable modeling routines allowing to successfully simulate e.g. complex grid structures (Figure 1) and to predict their mechanical behavior.

b) SLM process

- Optimization of the SLM process in order to minimize needed support structures and corresponding finishing operations as well as increase the productivity of the process. This opens the way for new design concepts.

c) Production equipment

- Development of an SLM-production environment with increased automation regarding machine handling, part unloading and separation from the base plate as well as part finishing.

d) TQM system

- Implementation of a comprehensive TQM system, as proposed by (Levy et al. 2007) ensuring reproducibility and reliability of the whole process chain.

e) Education

- Development of university courses at graduate and undergraduate levels and industrial training programs.

Such measures allow widening the fields of suitable application for Additive Manufacturing. Demonstrators and exemplary applications like the presented results will open the way to implement the new design possibilities into more real parts and raise the SLM usability and confidence level.

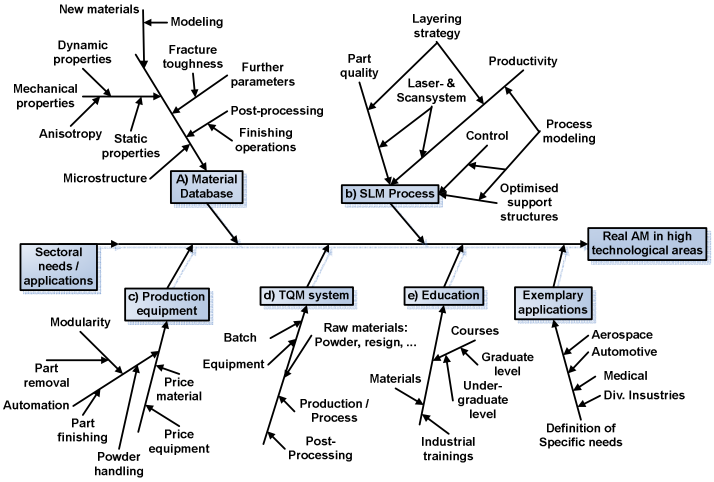


Figure 8: Ishikawa diagram: Fields of needed development

6 CONCLUSION

The aim of the case study was to demonstrate exemplarily that SLM design features and materials can be suitable for structural, load-bearing parts. It demonstrates that the static and dynamic mechanical properties already can meet the specific requirements of many applications. This principally allows the use of SLM for the production of end use parts in many industrial sectors in the sense of Additive Manufacturing. The results encourage further evolving the presented brackets towards extreme lightweight structures as shown in Figure 1. Furthermore, the very wide design possibilities of SLM allow creating lightweight structures e.g. in steel materials with around the same weight, but a considerably higher stiffness, strength (Figure 7) and fatigue strength compared to conventional structures in Aluminum.

However, there are also a number of challenging limitations that hinder a wider use of SLM for the production of functional parts, especially for sectors with high material requirements like aerospace, automotive or medical. Therefore the aim is to close the gap between the current technological state and required process- and production needs. An on-going effort with possibly increased support by national and international funding is crucial on the way to a wide-ranging success.

7 REFERENCES

Abe, F., Santos, E.C., Kitamura, Y., Osakada, K. & Shiomi, M. 2003. Influence of forming conditions on the titanium model in rapid prototyping with the selective laser melting process. *Proceedings Of The Institution Of Mechanical Engineers Part C-Journal Of Mechanical Engineering Science,* 217**,** 119-126.

Averyanova, M. & Bertrand, P. 2010. Direct Manufacturing of dense parts from martensitic precipitation hardening steel gas atomized powder by Selective Laser Melting (SLM) technology. In *Advanced Research in Virtual and Rapid Prototyping,* ed. P. J. e. a. Bártolo, 343-348. Leiria, Portugal: CRC Press / Balkema.

Badrosamay, M., Yasa, E., Van Vaerenbergh, J. & Kruth, J.P. 2009. Improving Productivity Rate in SLM of Commercial Steele Powders. In *RAPID*, 1-13. Schaumburg, IL, USA.

Bourell, D.L., Leu, M.C. & Rosen, D.W. 2009. *Roadmap for Additive Manufacturing - Identifying the Future of Freeform Processing*. Austin: The University of Texas at Austin - Laboratory for Freeform Fabrication.

Childs, T.H.C., Hauser, C. & Badrossamay, M. 2005. Selective laser sintering (melting) of stainless and tool steel powders: experiments and modelling. *Proceedings Of The Institution Of Mechanical Engineers Part B-Journal Of Engineering Manufacture,* 219**,** 339-357.

Christensen, A., Lippincott, A. & Kircher, R. 2007. Qualification of Electron Beam Melted (EBM) Ti6Al4V-ELI for Orthopaedic Implant Applications. In *Materials & Processes for Medical Devices (ASM International)*, 48-53. Palm Desert, California: ASM International.

Formula_Student_webpage. 2011. www.formulastudent.com.

CES EduPack.

Gravet, D. 2008. Hipermoulding: efficiency of conformal cooling. In *International Conference on Polymers and Moulds Innovations PMI*. University College Ghent, Belgium.

Gu, D. & Shen, Y. 2008. Processing conditions and microstructural features of porous 316L stainless steel components by DMLS. *Applied Surface Science,* 255**,** 1880-1887.

Herzog, F. 2008. LaserCusing technology optimises die casting dies. In *Casting Plant & Technology*, 18-20.

Klingbeil, N.W., Bontha, S., Brown, C.J., Gaddam, D.R., Kobryn, P.A., Fraser, H.L. & Sears, J. 2004. Effects of Process Variables and Size Scale on Solidification Microstructure in Laser-Based Solid Freeform Fabrication of Ti-6Al-4V. In *Solid Freeform Fabrication SFF*. Austin TX.

Kruth, J.P., Froyen, L., Van Vaerenbergh, J., Mercelis, P., Rombouts, M. & Lauwers, B. 2004. Selective laser melting of iron-based powder. *Journal Of Materials Processing Technology,* 149**,** 616-622.

Levy, G., Schindel, R., Schleiss, P. & Spierings, A.B. 2007. Quality Management Representation and Application for Rapid Manufacturing with SLS (Selective Laser Sintering). In *15th International Symposium on Electromachining (ISEM XV)*.

Lohmeier, K.M. 2005. Stahl- und Aluminiumteile: Praktische Erfahrungen mit generativem Prototyping. In *3. Swiss Rapid Forum*. St.Gallen.

Lopez, G., Williams, S., Miranda, R.M., Quintino, L. & Rodrigues, J.P. 2008. Additive manufacturing of Ti-6Al-4V based components with high power fiber laser. In *Virtual and rapid manufacturing,* ed. B. et.al, 369-374.

Mumtaz, K.A., Erasenthiran, P. & Hopkinson, N. 2008. High density selective laser melting of Waspaloy®. *Journal of Materials Processing Technology,* 195**,** 77-87.

Munguia, J. 2008. Pursuing successful Rapid Manufacturing in a standards-less industry: a best practice approach. In *Virtual and rapid manufacturing*, 477-481. Leira Portugal: Bartolo et al. (eds)

Rehme, O. & C, E. 2006. Rapid manufacturing of lattice structures with Selective Laser Melting. In *Laser-based Micropackaging, Proceedings of SPIE*

Santos, E.C., Osakada, K., Shiomi, M., Kitamura, Y. & Abe, F. 2004. Microstructure and mechanical properties of pure titanium models fabricated by selective laser melting. *Proceedings Of The Institution Of Mechanical Engineers Part C-Journal Of Mechanical Engineering Science,* 218**,** 711-719.

Sehrt, J.T. & Witt, G. 2009. Auswirkungen des anisotropen Gefüges strahlgeschmolzener Bauteile auf mechanische Eigenschaftswerte. In *Rapid.Tech*. Erfurt Germany: Messe Erfurt AG.

Sehrt, J.T. & Witt, G. 2010. Dynamic strength and fracture toughness analysis of beam melted parts. In *International MATADOR Conference*. Manchester, Lancashire, United Kingdom

Shellabear, M. 2008. Direct Metal Laser-Sintering of Titanium. NASA Tech Briefs May.

Simchi, A. 2006. Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features. *Materials Science and Engineering: A,* 428**,** 148-158.

Spierings, A., Starr, L. & Wegener, K. submitted. Fatigue performance of Additive Manufactured metallic Parts. *Rapid Prototyping Journal,* submitted.

Spierings, A.B., Herres, N. & Levy, G. 2010. Influence of the particle size distribution on surface quality and mechanical properties in additive manufactured stainless steel parts. In *Proceedings of the Annual International Solid Freeform Fabrication Symposium,* ed. D. L. Bourell. Austin, Texas.

Spierings, A.B., Herres, N. & Levy, G. 2011. Influence of the particle size distribution on surface quality and mechanical properties in additive manufactured stainless steel parts. *Rapid Prototyping Journal,* 17**,** 195 - 202.

Spierings, A.B. & Levy, G. 2009a. Comparison of density of stainless steel 316L parts produced with selective laser melting using different powder grades. In *Proceedings of the Annual International Solid Freeform Fabrication Symposium,* ed. D. L. Bourell, 342-353. Austin, Texas.

Spierings, A.B. & Levy, G. 2009b. Rapid Manufacturing - auch mit SLM. In *Rapid.Tech*. Erfurt, Germany: Messe Erfurt AG.

Starr, T.L. & Spierings, A.B. 2010. Tensile and Fatigue Performance of Laser Sintered Stainless Steels. In *Proceedings of the Annual International Solid Freeform Fabrication Symposium,* ed. D. L. Bourell. Austin, Texas.

Uckelmann, I. 2006. Generative Serienfertigung von individuellen Produkten aus CoCr mit dem Selektiven Laser Schmelzen. In *Fakultät für Maschinenwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen*, 110. Aachen: Technische Hochschule Aachen.

Villalon, A.V. 2005. Electron Beam Fabrication of Injection Mold Tooling with Conformal Cooling Channels 68. Raleigh: North Carolina State University

Yasa, E., Deckers, J., Kruth, J.P., Rombouts, M. & Luyten, J. 2010. Experimental investigation of charpy impact tests on metallic SLM parts. In *Advanced Research in Virtual and*

Rapid Prototyping, ed. P. J. Bártolo, 207-214. Leiria, Portugal: CRC Press / Balkema.