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FROM RAPID PROTOTYPING TO RAPID MANUFACTURING - AN INDUSTRIAL AND ACADEMIC PERSPECTIVE

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ABSTRACT: Using 3D Printing and Selective Laser Melting as representatives for the whole bunch of additive technologies the aim of this paper is to give a snap shot of its current state. Based on a brief analysis of their main characteristics the progress of this most innovative class manufacturing processes is highlighted. While selected applications from the past demonstrate their significance mainly for accelerated product development, most recent experiences illustrate their huge potential for improvement of industrial performance. Related challenges for academic and industrial research are pointed out. The paper concludes with a consolidated picture of the AM technologies within the work environment.

INTRODUCTION

Additive Manufacturing (AM) technologies have expanded vastly over the more than 20 years of its history. Originally seen as mostly suitable for Rapid Prototyping (RP), these processes are not exclusively used for that purpose any longer. With the advent of new materials along with new processes, each technology has been contributing to the diversities in different fields of application. In the process of improvement, it is however critical to understand what the capability of each individual technology is in order to compare current processes and techniques, or even future improvements.

In recent years Three Dimensional Printing (3DP) came to the foreground as a very competitive process in terms of cost and speed, and sales of related equipment have increased significantly compared to other AM machines (3D Printer sales from '05 to '10 have been extrapolated from Wohlers (2011)) (Figure 1). These devices were developed, and are still seen, mostly as a “concept modeller”. However, with the larger selection of materials available today, as well as the wide variety of post treatment procedures, the scope for this technology has grown quickly – far beyond the original idea of generating design iterations or inexpensive metal parts directly from a CAD file. On the other hand intensive research efforts have been focused primarily on the so called high-end additive processes, and above all on the Stereolithography (SLA) and the Selective Laser Sintering/Selective Laser Melting (SLS/SLM) technologies, exploring various issues mostly related to process control and material property improvement.

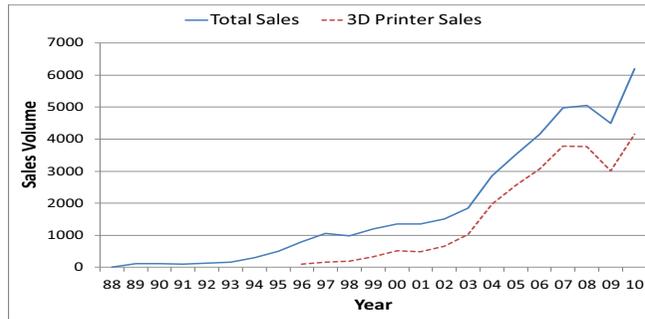


Figure 1. Growth of global AM equipment sales, Wohlers (2011)

In the context of this paper it is important to clarify the meaning of the different categories. According to Levy et al. (2003) the RP is a well-defined and justified application of AM technologies in the Rapid Product Development cycle. Rapid Manufacturing (RM) on the contrary is “the manufacture of end-use products by means of AM techniques (solid imaging)”. In contrast to RM, Rapid Tooling (RT) embodies the manufacturing of mould and dies, able to produce “several thousand or even millions of parts before final wearing-out”.

FROM RAPID PROTOTYPING TO RAPID MANUFACTURING – A BRIEF OVERVIEW

Additive Manufacturing progress development

Since the commercialization of the first AM machine, research endeavours have been made to improve various areas in its system hardware, software or materials. This has led to developing an aid to understanding process improvement and has been aptly referred to as “The Wheel of Progress” (Figure 2). The hill to be climbed is the increasing performance of Additive Manufacturing systems. The wheel that moves up this hill, if sufficient driving force is applied, has segments representing the hardware, software, building process, and materials used to make parts. Insight gained by using this model indicates that once a technique is configured with all four components in place, it soon becomes clear that one of the components is a limiting factor, impeding advancement up the metaphorical hill of progress. Continued research, development, and engineering attention to the appropriate topic eventually yields improved capability of that component, and allows the wheel to travel uphill a little further. But no sooner has that limitation been overcome than another takes its place. And so it continues. Improved hardware requires enhanced software, enabling better processing techniques, after which the materials will require upgrading.

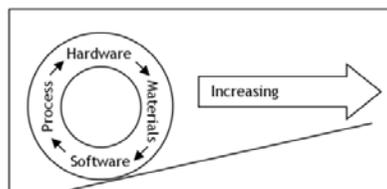


Figure 2. The Wheel of Progress, Jacobs (1996)

3D Printing

During the last 15 years a large variety of 3D Printing techniques were introduced into the AM industry. Depending on the method used, a thermal, polymer or physical phase change takes place. Table 1 shows how different deposition techniques link up to the different technologies.

Table 1. Summary of processes and corresponding technologies

Aimed Deposition Process	Technology
Drop-on-drop deposition	<ul style="list-style-type: none"> • 3D Plotting • Multi-Jet Modeling
Drop-on-powder deposition	<ul style="list-style-type: none"> • 3D Printing
Continuous deposition	<ul style="list-style-type: none"> • Fused Deposition Modeling (FDM)

The Drop-on-Drop (DoD) and the Continuous Printing have a similar character, namely the “printable fluid” and the building substance are one and the same material. This means that the building material has to meet two requirements – the first is related to the fluid’s printability, and secondly to the purpose of building the model, i.e. the intended application. The necessity to fulfill this set of requirements puts substantial limits to the range of materials suitable for a particular application. In contrast, the Drop-on-Bed (DoB) (Powder) version distributes the responsibility to meet the requirements to two different substances. In fact, almost every material can be brought to a powder state – the starting point also of the SLS process. Hereby the task to make this material possible to process in a 3DP device is moved to the task to find a suitable binding liquid. This scenario predetermines a much larger variety of suitable combinations and thus, a much larger application range. The possibility to use infiltrating agents in a next stage of the model manufacturing process further extends the variety of applications. This fact is illustrated by the conceptual diagram below (Figure 3), which depicts the areas of application in relation to the quantity of machine units sold (based on Wohlers (2011)) for each of these 3DP techniques. Printer machines that make use of the Continuous Printing technique have by far (in the order of almost 3 times) exceeded the sales volumes of those that make use of DoD or DoB techniques. However printers using the DoB technique span over a wider range of applications.

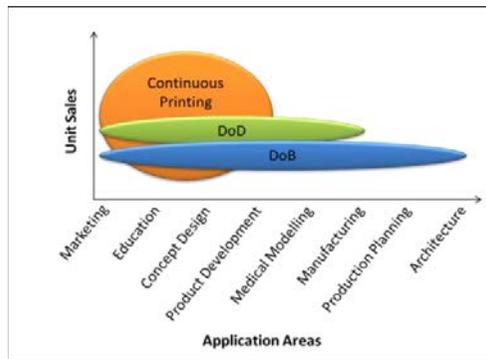


Figure 3. Conceptual depiction of machine unit sales and areas of application

Selective Laser Sintering/Selective Laser Melting (SLS/SLM)

One of the main concerns when utilising SLS/SLM technologies is the achievable mechanical properties. The material performance of SLM produced parts depends on numerous factors that

include material powder characteristics, such as viscosity, melting temperature, particle shape, particle size, composition and thermal conductivity, process parameters such as laser power, scan speed, thickness, hatch spacing and angle of construction, a combination of the material and process parameters such as absorptive/reflectivity, bed temperature distribution and molten pool size, and post-processing procedures such as heat-treatment and hot isostatic pressing, i.e. Vandenbroucke & Kruth (2007), Van Elsen et al. (2008), Vrancken et al. (2012).

Numerous studies have researched the material performance of SLM produced materials. This includes various steels and titanium alloys such as Ti6Al4V, e.g. Kruth (2005), Li et al. (2010). Typically, porosity, high residual stresses due to the inherent high temperature gradients, quasi-static, dynamic and crack growth characteristics, and the microstructural interaction with respect to the aforementioned are of interest.

The material performance of SLM processed materials has been shown to compare well to its equivalent wrought counterpart. However, the technological requirements within the context of achievable material performance are application specific and, in many instances, concerns over porosity, microstructure and high residual stresses exists. According to ASTM F1472, for example, as-built SLM Ti6Al4V biomedical implants are not allowed due to the presence of a martensitic microstructure and limited ductility, Vrancken et al. (2012). Similarly, the presence of porosity has shown to have a significant effect on the fatigue life, Leuders et al. (2013), which when considering the aeronautical industry can have detrimental consequences.

To obtain an understanding of the material performance of SLM produced materials and its link to the process methodology requires a substantial experimental programme. Often material properties, single process parameters, post processing techniques such as heat treatments are undertaken to help better understand the link between the SLM process and achievable properties. However, to date no complete understanding exist that can confidently predict the material performance and integrity of SLM produced parts.

In a recent study the achievable mechanical properties of LaserCusing produced tool steel CL50WS and titanium alloy Ti6Al4V samples were investigated. Heat treatments were used to tailor properties which are compared to their wrought counterpart.

The measured mechanical properties are summarised in Table 2. A density of 99.5% is typically achieved using the M2 LaserCusing system. Porosity as well as high irregular residual stresses (up to yield strength) do not have a strong impact on the tensile strength. Following heat treatment residual stresses are readily minimised and tensile properties similar to the wrought material can be achieved.

The microstructural study has shown that as-built conditions result in a fine microstructure due to a very high cooling rate and rapid solidification. This microstructure, however, may be tailored through heat-treatment to achieve somewhat desirable microstructure and properties. The enhanced quasi-static properties seem to be influenced by the changes in microstructure, i.e. grain size and phase fractions.

Fatigue properties seem similar to the wrought material after heat-treatment, as shown in Figure 4. However, a peculiar interaction exists between porosity and fatigue life. Results obtained from fatigue tests on Ti-6Al-4V indicated that porosity significantly reduces the fatigue strength, compared to annealed samples. This is in agreement with the work done by Leuders et al. (2013),

Table 2. Summary of material properties

Process technology	Yield Strength [MPa]	UTS [MPa]	% elongation	K_{Ic} [MPa√m]
CL50WS, as build condition	900-1050	1010-1205	8.3-12.1	-
CL50WS, solution anneal	800-815	950-1000	11.8-12.5	-
CL50WS, solution anneal & age hardened	1720-1790	1800-1850	4.4-5.1	-
Wrought material, solution anneal & age hardened	1790-2070	1830-2100	5-10	-
Ti-6Al-4V, as build condition	1100-1150	1215-1260	7.2-8.9	28-34
Ti-6Al-4V, recrystallization anneal	890-900	950-965	10.7-11.7	66-67
Ti-6Al-4V, mill annealed	-	930-970	17-19	44-66
Ti-6Al-4V, beta annealed	-	875-915	-	88-110

who showed that the mean stress based fatigue life ranged from $27 \cdot 10^3$ to $290 \cdot 10^3$ cycles to failure for as-built and heat-treated samples. By contrast, none of the HIPed specimens failed during tests, which were interrupted at $2 \cdot 10^6$ cycles at a cyclic stress of 600 MPa.

From the discussion above it is evident that the correct heat-treatment forms part of successful implementation of SLM parts in industry. Some concerns regarding the fatigue performance and quality control remain.

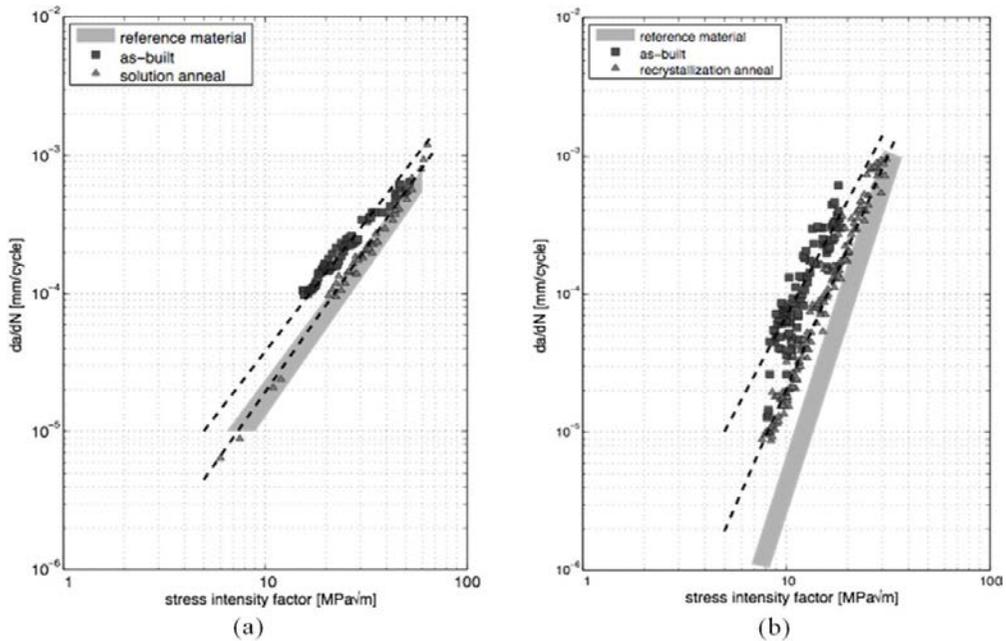


Figure 4. Crack growth behavior for (a) CL50WS and (b) Ti-6Al-4V. Data shows the as built and heat-treated condition.

INDUSTRIAL APPLICATIONS

Applications of 3D Printing

Contrary to popular opinion from previous years, 3DP processes are currently used in a wide variety of applications. By considering some applications, it becomes clear that through the improvements of hardware, materials and software, as depicted in the “Wheel of progress”, new applications became possible with the subsequent improvement in 3DP processes.

Design and Proof of Concept

This was the original intention of 3DP and therefore one of its main strengths. The comparatively low capital cost of the systems and fast printing times are ideally suited to quickly create physical models during any design stage. These physical models enhance communication, especially between engineers and non-engineers and are an additional tool that can be used to minimize design errors. One such example is a case in which 3DP aided the design of the core system of a marine engine gearbox by allowing a half scale mock-up of the pattern and core system (Figure 5(a)). This facilitated discussion and planning of the core system, ensuring that sufficient support was provided for all cores, checking the wall thickness, deciding on the core layout and the number of required cores. This is invaluable in bringing designers, pattern makers and foundry personnel together as a concurrent engineering design team.

Furthermore, the ability of 3DP to now print in colour can add a lot of value in design communication. Colours can be used to represent non-geometrical information, e.g. the results of a stress analysis, draft angles, highlighting landmarks, etc. (which cannot necessarily be painted on afterwards). Or it can simply be used to represent the final printing and/or painting of the component. No matter how it is used, it is a cost efficient means of adding value to prototypes early in the design phase.

Functional Prototypes

The purpose of these models is to test the fitment in a larger assembly or to test one or more of the functions of a product. For functional testing, some of the prototype’s material properties need to closely match the end use material, e.g. its yield strength, hardness, elasticity, water resistance, heat resistance, etc. The accuracy of the prototype must also be within acceptable limits. Where 3DP materials and process limitation precludes the use of these prototypes for this purpose, some secondary processes can be employed. An example where 3DP was very successfully used for pattern making for sand moulds is shown below (Figure 5(b)). From these moulds several castings of automotive engine brackets were produced within the acceptable tolerance as prototypes for functional testing of the power train before the final die castings were produced.

Medical modelling

Since its initial application of being merely a visual aid for surgical planning the use of 3DP in the medical field has grown significantly to include, among others, patient specific orthopaedic and craniofacial implants, guides for surgical procedures, scaffolds for tissue engineering and drug delivery systems for pharmaceutical administration. Anatomical models (or medical models) however still remain the most commonly used medical application of the 3DP process. These models are physical replicas of patients’ hard or soft tissue anatomy. They help surgeons to improve their planning of complex surgical procedures, which results in a reduction of surgical time and more predictable surgical outcomes (Figure 5(c)), Honiball, (2010). They are useful in the pre-bending of metallic reconstruction plates, creating patient-specific facial implants, and for measuring and fitting devices used during other reconstructive surgeries.

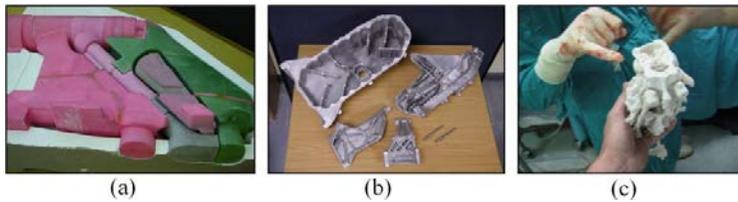


Figure 5. (a) Core layout development, (b) Sand cast prototypes of automotive engine brackets and oil sump for functional testing and (c) Medical model used during revision surgery showing the spine and previous implants

Applications of SLM Technologies

Conformal cooling for Rapid Production Tooling

Figure 6 illustrates the insert for a mould of a cutlery drainer. The designed cooling was first simulated to ensure that there would be no hotspots. The insert was machined from solid and all the straight cooling channels drilled from the top. Only the top 10mm was laser-cused to form a honeycomb structure that connects all the drilled holes, making this a hybrid part. This new solution for an existing product brought a 31% reduction in cycle time leading to a substantial productivity increase.

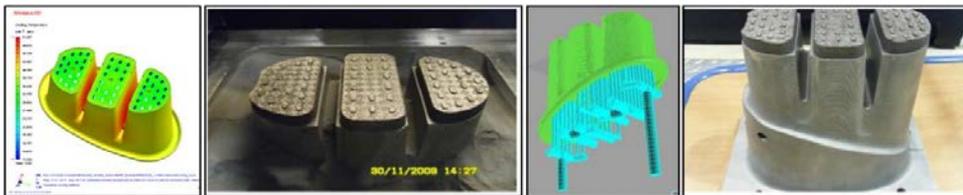


Figure 6. Cutlery drainer insert with conformal cooling – hybrid part (Toolsteel)

Intelligent implants

In the past decade, various studies have investigated the possible applications of metal additive manufacturing (AM) for the fabrication of a diverse range of medical implant devices for fracture fixation, dental, orthopaedic, and cardiovascular prostheses, Bartolo et al (2012), Sündermann et al. (2013). In recent years however, these applications have begun to realise in human patients and the innovative use of metal AM for production of custom medical devices is gradually on the increase.

An area where AM can enhance the functionality of medical implants is in reducing the risk of implant infection. Implant infection is currently still a devastating complication, which initiates through colonisation of bacterial pathogens onto the biomaterial. By preventing bacteria from colonising onto the implant, human osteoblasts can successfully integrate with the material, greatly reducing the risk of infection. The cubic specimens visible in Figure 7(a) have been manufactured for this purpose. The specimens have internal channels to act as drug reservoirs, eluting antimicrobials from within the implant to prevent bacterial colonisation. For proof of concept purposes, commercial antibiotic bone cement (Palacos R+G, Heraeus Medical GmbH) containing gentamicin, have been used as drug delivery material. Figure 7(a) shows specimens loaded with Palacos R+G before challenged with a gentamicin susceptible *Staphylococcus aureus* Xen 36 strain. In Figure 7(b) the zone of inhibition (693.15 mm^2) after 24 hours is clearly visible. This

preliminary result is very positive, since it is argued that the first 6-8 hours post implantation is a critical period during which colonisation must be prevented.



Figure 7. (a) Colonisation prevention samples enforced with antibiotic loaded bone cement (b) clearly visible zone of bacterial inhibition around a colonisation prevention sample

RESEARCH CHALLENGES

Intensive research is conducted towards the enhancement of the 3DP process. A large portion of this type of research is related to the improvement of the basic process capabilities with regard to the achievable accuracy and surface quality.

Substantial efforts are focused on the development of advanced control strategies. One of the most important issues in this domain is the development of the Local Composition Control (LCC). The LCC represents basically the ability to create objects with composition variation within them. This indicates the great potential to produce parts whose material composition can be tailored within a component to achieve local control of properties (e.g. index of refraction, electrical conductivity, formability, magnetic properties, corrosion resistance, hardness vs. toughness, etc.). Another issue in this regard is the adaptive slicing control, which generates different slice thicknesses based on the local slope of the part, Hiller & Lipson (2010).

A significant improvement in the material performance of SLM produced parts can be achieved by an appropriate heat treatment from a residual stress, ductility, toughness as well as the crack growth characteristics point of view. However, standard heat treatments may not apply to SLM produced components. In Ti-6Al-4V, for example, the microstructure and hence the mechanical properties depend on the process history. Since, as-built SLM Ti-6Al-4V has a fine acicular morphology arising as a result of the heating above the β transus temperature, thus improper heat-treatment can result in undesirable properties.

Furthermore, parts produced using the SLM technology have some degree of residual porosity, which can adversely affect the mechanical properties from a fatigue life perspective. Porosity and microstructure interfaces can provide loci for crack initiation and propagation and thereby leading to premature failure, Lauders et al., (2013). Further investigations are required that study the relationship between crack growth threshold values, fatigue life, porosity and the microstructure interaction.

The detrimental effects on fatigue strength due to the random porosity of AM parts are still a challenge for application to load bearing devices such as hip replacement stems. The surfaces generated by these processes reveal an inherently rough and porous structure due to the partial sintering of adjacent powder particles onto the substrate. Instead of designing complex ad hoc lattice structures onto the surface with a multitude of sharp corners that are undesired stress concentrations, investigations into utilising the partial sintered powder particles as a resultant

porous structure could also be beneficial for both bone ingrowth and reduction in manufacturing time of implants. The challenge arises in preparing this layer in such a way as to conform to international standards for medical implants. Another challenge for *in vitro* testing is the use of decaying cadaver bone specimens. Although animal studies can provide insights into tissue response and bone growth onto the materials, compression tests such as discussed above, have to be performed on parts as close as possible to the geometry and orientation of human bone.

CONCLUSION

Extensive market research shows that the 3D Printing process is the most widely used additive manufacturing method in the professional world. While the Continuous Printing technique as utilised predominantly in the Fused Deposition Modelling process is responsible mostly for the high sales numbers narrowed on certain applications such as concept design and visualisation, the Drop-on-Bed version is characterised by large variety of applications covering art, education, architecture, medical and industrial fields. Thus the question of continuous update of the capability profile of this process is of paramount importance for current and potential users – designers, educators, medical practitioners, manufacturing engineers, architects.

The SLM processes yield a high density of 99.8 % which can be further improved to a near full density (99.94 %) by appropriate post treatment. In order to reduce porosity optimised scan spacing has to be used. Residual stresses can be substantially reduced by an optimised layer building strategy. Significant improvement in the material performance of SLM produced components can be achieved by an appropriate post treatment. The various possible procedures, however, applying different heat treatment conditions have to be investigated in a specific context and their impact on the final product qualities evaluated from technological and economical perspective. In this way the opportunity potential for most demanding applications can be wide open.

And finally, how relate the different AM technologies among each other in the wide field of possible applications from RP right through to the RM? A conceivable scenario is shown in Figure 8, which to a large extent was confirmed by the developments during the past decade. A firm lace of the 3DP technology will remain during the design phase. The big potential, however, in the rapid manufacturing domain manifests particularly for the SLM process its great future perspectives.

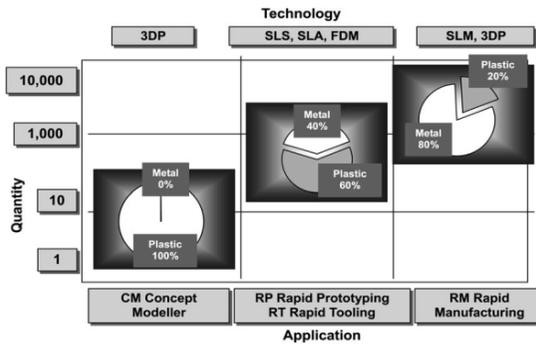


Figure 8. Consolidation forecast for the AM Technologies 2002-2010 (Levy et al., 2004)

REFERENCES

- Bartolo, P., Kruth, J. P., Silva, J., Levy, G., Malshe, A., Rajurkar, K., Mitsuishi, M., Ciurana, J., Leu, M. (2012). "Biomedical production of implants by additive electro-chemical and physical processes", *Annals of the CIRP – Manufacturing Technology*, 61, 635-655.
- Hiller, J., Lipson, H. (2010). "Tunable Digital Material Properties for 3D Voxel Printers", *Rapid Prototyping Journal*, 16, 241-247.
- Honiball, R. (2010). *MScEng Thesis: The Application of 3D Printing in Reconstructive Surgery*. Stellenbosch, Stellenbosch University
- Jacobs, P. (1996). *Stereolithography and other RP&M Technologies*, New York: ASME Press
- Kruth, J. P., Mercelis, P., Van Vaerenbergh, J., Froyen, L. & Rombouts, M. (2005). "Binding mechanisms in selective laser sintering and selective laser melting", *Rapid Prototyping Journal*, 11(1), 26-36.
- Leuders, S., Thöne, M., Riemer, A., Niendorf, T., Tröster, T., Richard, H. A., & Maier, H. J. (2013). "On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance", *International Journal of Fatigue*, 48, 300-307.
- Levy, G.N., Schindel, R., Kruth, J. P. (2003). "Rapid Manufacturing and Rapid Tooling with Layer Manufacturing (LM) Technologies, State of the Art and Future Perspectives", *Annals of the CIRP*, 52 (2), 589-609.
- Levy, G.N., Schindel, R., Frenzel, R. (2004). Customer Demands versus Concept Modellers – Performance Actual CM Systems, *Proceedings, Rapid Tech Conference*, May, Erfurt, Germany.
- Li, R., Liu, J., Shi, Y., Du, M., & Xie, Z. (2010). "316L stainless steel with gradient porosity fabricated by selective laser melting", *Journal of Materials Engineering and Performance*, 19(5), 666-671.
- Sündermann, S.H., Gessat, M., Cesarovic, N., Frauenfelder, T., Biaggi, P., Bettex, D., Falk, V., Jacobs, S. (2013). "Implantation of personalized, biocompatible mitral annuloplasty rings: feasibility study in an animal model", *Interactive CardioVascular and Thoracic Surgery*, 16, 417-422
- Vandenbroucke, B. & Kruth, J. P. (2007). "Selective laser melting of biocompatible metals for rapid manufacturing of medical parts", *Rapid Prototyping Journal*, 13(4), 196-203.
- Van Elsen, M., Al-Bender, F. and Kruth, J.P. (2008). "Application of dimensional analysis to selective laser melting", *Rapid Prototyping Journal*, 14 (1), 15-22.
- Vrancken, B., Thijs, L., Kruth, J. P., & Van Humbeeck, J. (2012). "Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties", *Journal of Alloys and Compounds*, 541, 177-185.
- Wohlers, T. (2011). *Additive Manufacturing: State of the Industry*. Fort Collins, Colorado