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Procedia CIRP 36 (2015) 230 – 235

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CIRP 25th Design Conference Innovative Product Creation

Design Strategies for the Process of Additive Manufacturing

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Abstract

Additive manufacturing (AM) is a cyclic manufacturing process to create three-dimensional objects layer-by-layer directly from a 3D CAD model. Today AM processes like SLM and SLS are already suitable for direct part production. The processes have little restrictions regarding the shape of the object. The challenge to a designer is to use the unique characteristics of additive manufacturing in the development process to create an added value for the manufacturer and the user of a product. This paper presents two design strategies to use additive manufacturing's benefits in product development. A manufacturing driven design strategy allows a substitution of manufacturing processes at a later stage of the product life cycle, while a function driven design strategy increases the performance of a product. The choice of strategy has great impact on the development process and the design of components. Two cases are presented to explain and illustrate these design strategies.

Peer-review under responsibility of the scientific committee of the CIRP 25th Design Conference Innovative Product Creation

Keywords: Design for Additive Manufacturing; Additive Manufacturing; Design for X; Design Strategy; Selection Criteria

1. Introduction

Additive Manufacturing (AM), or 3D printing as it is referred to in the media, is a group of manufacturing technologies which are capable to produce complex, three-dimensional objects without the need for individual tooling. Since the beginning of the 1980s additive manufacturing evolved from the first processes for the rapid production of prototypes into a number of different processes of which some are capable of direct part production. Today processes like selective laser melting (SLM), selective laser sintering (SLS) and with some limitations fused deposition modelling (FDM) are capable to produce direct parts in end-user quality out of metal or thermoplastics. Additive manufacturing processes are technologically mature for industrial production and due to a rising competition between service providers additive manufacturing becomes economically feasible for a growing number of industrial and end-user applications [1]. From a design perspective the challenge of additive manufacturing is to understanding the limitations and opportunities of these new processes and to use them in the right applications. This paper supports the designer to select a suitable design strategy for the development of new products and the improvement of existing ones.

2. Additive manufacturing processes

Before a designer is able to create a truly additive design he needs to understand the characteristics of additive manufacturing. The common standard of ASTM and ISO defines additive manufacturing as a manufacturing process to produce three-dimensional objects by adding material layer-by-layer. The production is based on a 3D model which is digitally sliced into layers. [2]

There is a growing number of AM processes available with different processes to join material. Each process is limited to one type of material and only few are able to process more than one material e.g. thermoplastics of different color [3,4]. In the last decade the maturity of these processes was largely increased due to research on new materials, development of better equipment and a deeper understanding of the processes which led to robust and stable processes [4]. From an industrial perspective processes capable of producing robust parts with high strength and long-term stability are most

Peer-review under responsibility of the scientific committee of the CIRP 25th Design Conference Innovative Product Creation
doi:10.1016/j.procir.2015.01.082

relevant, because they allow the direct production of end-user parts.

Two processes which meet this requirement are Selective Laser Melting (SLM) for metallic parts and Selective Laser Sintering (SLS) for thermoplastics. Both processes are based on the principle of powder-bed fusion. Figure 1 depicts the cyclic process consisting of applying a layer of powder, solidifying the powder with the energy of a laser beam and lowering the powder-bed for the next layer to be applied.

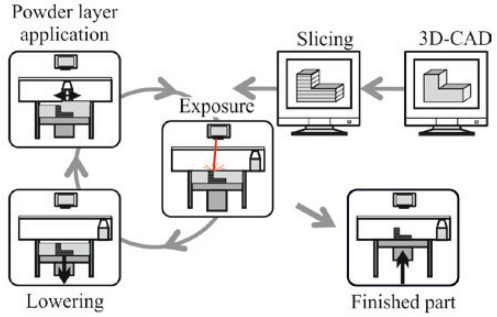

Fig. 1. Additive manufacturing by laser-based powder-bed fusion [5]

Parts produced by SLS and SLM have similar material properties compared to conventional parts of the same material. There is a slight anisotropy between the strength in build direction and the ones in perpendicular directions, but this is usually neglected in design. [6, 7]

Fused Deposition Modelling (FDM) follows a different principle. A thermoplastic filament is extruded through a heated nozzle and placed on the previously build portion of the part. The mechanical properties of FDM parts are highly anisotropic and this should be respected in design. [8, 9]

3. Benefits of Additive manufacturing

The advantages of additive manufacturing as a manufacturing technology mainly derive from the basic principle of adding material in a cyclic process based on a 3D CAD-model without the need for any tools or fixtures. This basic principle has two effects on manufacturing costs.

First of all a complex three-dimensional object is broken down into simple two-dimensional manufacturing steps. Therefore the complexity of the part no longer dominates manufacturing time and costs. The complexity has some influence on the amount of support structures required in SLM and FDM, but it is not as dominant as in conventional processes. This is commonly referred to by the term *complexity for free*.

The second major difference between AM and conventional processes is the limited impact of lot size on manufacturing cost and lead time. Additive Manufacturing is a CAD driven process without the need for individual tooling or CAM programming. Without this upfront investment in production means producing a number of identical parts or the same amount of individual items takes the same effort. This *cost advantage at small lot sizes* allows the production of single parts and mass customization at reasonable costs.

Great expectations were raised in the past on how additive manufacturing will change the landscape of manufacturing [10]. Despite the quality of the produced parts and the growing productivity of the equipment it is unlikely for additive manufacturing to substitute traditional manufacturing processes in general [11]. Instead additive manufacturing is already a valuable extension to existing production technologies. The processes offer an almost unlimited freedom in design and an economic production of individual parts and by this AM helps to overcome the limitations of conventional processes. At the same time additive manufacturing is often more expensive compared to the costs per part volume of conventional processes. The challenge for a designer is to identify parts and assemblies where using the freedom of design creates an added value and by this justifying the additional costs of additive manufacturing.

A literature review reveals a number of different approaches to describe and cluster the benefits of additive manufacturing. Based on example of end products Gebhard (2013) demonstrates the larger freedom in design, which enables the integration of functions and the use of innovative design elements, a simple way of mass customization as well as a way to create novel materials and innovative manufacturing strategies [3]. Wohlers (2013) clusters direct part production into reduction of tooling, agile manufacturing operations, reduction in inventory, decentralized manufacturing, part consolidation, light weighting und lattice structures. He derives these clusters from case studies which also demonstrate that additive manufacturing is already capable to produce industrial goods [4]. Other publications, like Gausemeier et al. (2012) and Uglow et al. (2013), further distinguish the potential benefits of additive manufacturing between different applications or industries[11, 12].

4. From AM benefits to selection criteria

To use the benefits of additive manufacturing it is necessary to identify parts in a product where additive manufacturing's benefits create the most value to the customer. Companies continuously develop their products in order to maintain their market position. The objective behind product improvements or optimizations may vary. Typical examples are an increase of performance, a better efficiency or the reduction of costs.

One possible route to an improved product is a change of production technology. Additive Manufacturing is a young production technology which is deemed to offer new ways in product development. Today additive manufacturing processes are proven manufacturing technologies for serial products for industrial and end user applications [11]. Designers should consider using the advantages of additive manufacturing to create an added value for the user of their product.

Studying cases of successful AM parts and reading about its benefits might inspire designers for new designs, but it doesn't provide guidance in finding the right applications for additive manufacturing within the product portfolio of a company. A designer might even feel swamped by the multitude of possibilities and it clearly is difficult for him to

use the described cases of successful applications to solve a specific task. This is especially true for the first step on the way towards an additive manufactured part: to select the right part of a specific product to be manufactured by AM either without any changes or after a re-design. This decision is even more difficult for the large number of companies, which have not used additive manufacturing yet and therefore have no experience from previous AM projects.

The authors of this paper follow the approach to assist companies during the development of a first additive manufactured part for a serial product in order to build up knowledge and experience within their organization. They presented in Leutenecker et al. (2013) and Klahn et al. (2014) a guiding principle for the identification of suitable parts and assemblies in an existing design, as well as during the development of a product from scratch [13, 14]. The identification is done by the designers, because they are the experts for the systems and have detailed knowledge on the functions of the components as well as on the challenges of the application. The guiding principle clusters the potential benefits of additive manufacturing in four selection criteria based on the main objective of the design for additive manufacturing: integrated design, individualization, lightweight design and efficient design. The goal of the selection criteria is to reduce the multitude of potential benefits to four criteria which are easy to comprehend and memorize.

The four selection criteria were taught in trainings and at public events. They were presented together with industrial case studies to demonstrate the application of the criteria in the selection process and to give the audience an inspiration for designing a successful additive manufactured part in their company. The selection criteria proved to be useful in a number of industrial and academic projects. A very positive feedback was given by development projects that started from scratch or targeted a specific challenge in a given design. In these projects the selection criteria led the designers to parts and assemblies where a change of production technology gives additional freedom in design to tackle challenges. In these scenarios the number of parts in scope is limited and the people involved in the development project are familiar with the design, therefore they were able to perform a manual selection process.

In other projects the task was to screen the whole product portfolio of a small or medium sized company. More people were involved in these projects and the number of parts in scope was higher. To cope with a screening process of this scale the task was handed down to departments to reduce the scope for each group involved in the project. Each department received a presentation with instructions on additive manufacturing and the use of the selection criteria and a template to describe the identified parts. The template summarized the profile of each part and contained basic data like part dimensions, material and lot size plus a description of the expected benefits from changing the production to additive manufacturing. A group of additive manufacturing experts evaluated the profiles and categorized them in four groups:

- a design for additive manufacturing will bring a benefit,
- risks and expected benefits of additive manufacturing require a closer evaluation,
- the part can't be manufacture by AM in the near future because of dimensions, costs or other restrictions, and
- parts with no expected benefits.

The last category of parts with no benefits is usually was void after the evaluation. Therefore it is included here mostly for completeness.

The experience gained from the screening projects shows clearly that the selection criteria are well suited for small and medium sized projects, where the focus is on solving a problem with the advantages of additive manufacturing. Larger Projects to screen the products of a whole company are of a different type, because of its size and also the focus shifts towards finding problems for a given solution. Here the quality of the results depends too much on having dedicated persons throughout the company.

To improve the screening process the search has to become more systematic and the criteria need to be more detailed. This will allow a pre-selection based on data in an Enterprise Resource Planning (ERP) database. A general characteristic of such an ERP based selection is that it only points to a possible application for AM. The evaluation of the indicated parts or assemblies remains with a skilled professional. He will assess the potential of additive manufacturing with respect to the application and the user's requirements.

5. Design strategies for AM

The identified components, whether they are from an existing or novel product, can use the benefits of additive manufacturing by following two different design strategies. This choice determines the development process and should be made carefully. Either the designer uses additive manufacturing only as a manufacturing technology with cost benefits at complex parts and small lot sizes, or he also uses the advantage of AM's little restrictions on manufacturability. To clarify the different nature of these strategies and highlight the implications of the choice made both are explained in the following.

5.1. Manufacturing driven design strategy

The manufacturing driven design strategy uses additive manufacturing as a production technology. In this strategy the benefits of using additive manufacturing are derive from a substitution of manufacturing processes. By following the manufacturing driven design strategy the designer maintains a conventional design and complies with the design rules of other manufacturing technologies.

Rapid Prototyping was the first application of additive manufacturing and uses AM's process advantages. A part, designed for conventional production, is manufactured additively for time and cost reasons during the development process. [4]

The manufacturing driven design strategy can also be used in series production especially to mass customize a product.

Very prominent examples are additive manufactured dental implants [15]. The shape of implants was not altered when going from conventional casting or milling processes to additive manufacturing. The dental labs only use the flexibility of AM to produce an individual, freeform object for each patient at lower costs.

Another example of a manufacturing driven design strategy is the direct production of thermoplastic parts. Without the need to invest in an injection molding tool small series for niche markets become economically feasible. Companies can also reduce the risk of the ramp up of a new product. Instead of ordering a mold upfront the product is launched with additive manufactured components. The company can easily adjust the design according to the feedback of the first customers. Once the product is successfully launched and a stable design is reached, the production can be scaled up and transferred to a mass production process like injection molding. This transfer is only feasible, if the design complies with the design rules of the conventional manufacturing process.

5.2. Function driven design strategy

The function driven design strategy exploits the characteristics of AM to improve the functions of a product. Using the full potential of additive manufacturing‘s freedom in design usually rules out the transfer to conventional manufacturing without major adjustments to the design.

The decision for additive manufacturing of the end product should be made at the beginning of the development process. At this point in time only few limitations are defined and the design can follow the functions of a part. The resulting design often contains complex internal structures or integrated joints which are impossible to manufacture conventionally. An example for such a design is the medical device for shockwave therapy which was presented in Klahn et al. (2014) and is depicted in figure 2. Handling properties, assembly and shockwave generation were largely improved by using the freedom in design of additive manufacturing [14].

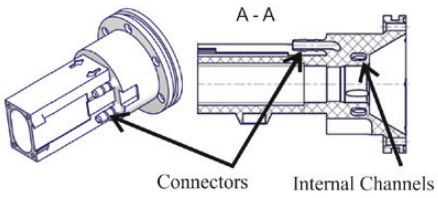

Fig. 2. Additive manufactured shockwave reflector of a medical device [13]

6. Case studies on the design strategies

Two case studies are described in the following to illustrate the different nature of manufacturing driven and function driven design strategies. The first case presents an add-on for whiteboard markers which is conventionally designed and benefits from the option to change between conventional and additive manufacturing. The second case study describes a function oriented re-design of a jigsaw base.

6.1. Case study of a manufacturing driven design strategy

The case of the Memox cap for whiteboard markers describes the manufacturing driven design strategy. The purpose of this add-on is to enable an intuitive and easy to use way to place a marker on a whiteboard. The solution provided by the Memox is a little add-on for the marker that attaches a magnet to the tip of a cap. The basic requirements of the product development process were to attach the pen to the whiteboard and to be easily adaptable to any commercially available board marker.

During the development of the add-on a Fused Deposition Modeling (FDM) printer was used for short iterations. Different designs with variations of magnets and shapes where created for handling tests. A small series of 50 pieces was produced by Selective Laser Sintering of PA12 for the first customer acceptance test in an office environment. The initial design is depicted in figure 3.

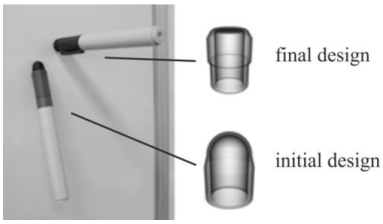

Fig. 3. Initial board marker cap design (bottom) and design after customer feedback (top)

Selective Laser Sintering was chosen because the robustness of FDM parts was only sufficient for prototypes in the development phase and injection molding involves high tooling costs. The customer test showed a good handling and usage of the marker, but the writing performance of the marker deteriorated quicker than usual. An analysis identified the improper storage of the markers on the whiteboard as the root cause for the shorter product life. Due to the hemispherical shape of the initial design the tip of the marker points upwards and this leads to premature drying out. This was be remedied by a change of cap and magnet geometry. The final design of the add-on cap ensures a horizontal position of the marker. Both the hemispherical initial design of the cap and the cylindrical final design are shown in figure 3 together with the resulting orientation of the marker on a whiteboard.

The short iterations of the design and the first costumer test allowed a short development time and a robust design at the start of series production. Finding the right manufacturing technology for a quick ramp-up of this innovative product was the next step. For the successful launch of the product into the market a rapid availability of the product at a competitive price is important. A direct comparison shows significant difference in the cost. To create reliable date on manufacturing costs different companies were asked for a quotation to produce a pilot series of given numbers of caps in less than 3 month. The offers are summarized in figure 4. The AM service provider offered to produce the add-on caps in SLS. Prototype tooling companies (1) and (2) offered injection molded prototypes, with a delivery time of three weeks. These

three companies offered only the production and delivery of parts. The forth company is a mold manufacturer for series production and offered an injection molding tool made from tooling steel and also to produce the parts. Due to the higher complexity of an injection molding tool for series production a delivery time of 3 months is expected.

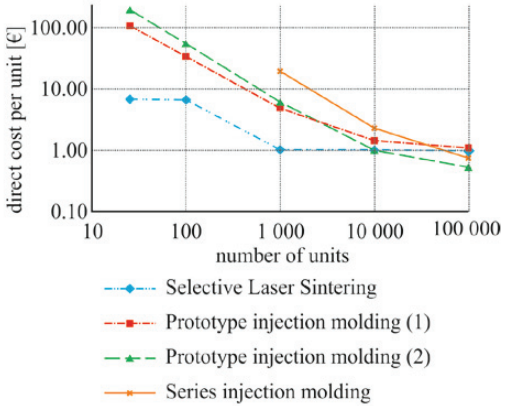

Fig. 4. Costs per unit of different lot sizes and manufacturing processes

Figure 4 shows clearly that the cost of a pilot series of 1 000 pieces is significantly lower with AM (SLS) than with injection molding. In the presented case even the AM production of up to 10 000 units is more favorable than injection molding. At higher batch sizes the investment in tooling pays off and conventional injection molding is more favorable in costs.

At this point the importance of distinguishing between manufacturing driven and function driven design strategies becomes clearer. The design of the add-on caps complies with the rules of conventional manufacturing methods, in particular the ones for injection molding. This allows changing the production process for mass production of the Memox add-ons for board markers.

Finally, it should be noted that this case shows clearly that additive manufacturing is not limited to product development and testing. Especially for the launch of a product its high flexibility and cost advantages for smaller quantities make additive manufacturing a suitable method for the series production. When a transfer to conventional manufacturing is planned at a later stage, it is advised to choose a manufacturing driven design strategy.

6.2. Case study of a function driven design strategy

Deciding at the beginning of a development process to use additive manufacturing as the only production technology allows full use of the design advantage of AM. The following re-design of a commercially available jigsaw's base illustrates this approach. An initial analysis of the sawing process revealed that the sawdust blower of the jigsaw provides a clear view on the cutting line. The installed saw dust extraction, however significantly reduces the sawdust transport and thus contaminates the work piece with a considerable amount of sawdust. One reason for this is the positioning of the blower and extractor openings on the evaluated jigsaw model. Both are located in the body of the jigsaw, behind the jigsaw blade and well above the work piece. The goal of the re-design was to improve these functions by relocating or redirecting both the sawdust blower and the dust extraction from the jigsaw body in the base. As an additional function a valve for the dust blower was implemented in the jigsaw base. The air comes from the body of the jigsaw and is either directed to the cutting area or vented at the side of the base.

First simple test with this arrangement showed a significant reduction in pollution on the work piece. Based on these results, the positioning of the ducts in the re-design of the jigsaw base was carried out. The function oriented design is depicted in figure 5. By positioning the sawdust blower directly opposite of the extraction both act in the same direction. The flow of air transports the sawdust into the extraction and the performance of the system is improved.

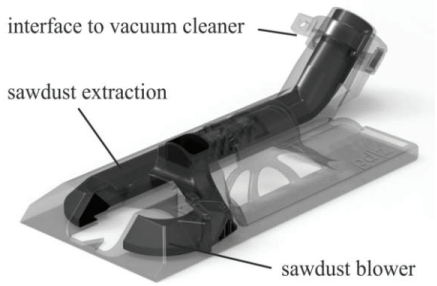

Fig. 5. Function oriented design of internal ducts

It was decided to design the base to be manufactured by Selective Laser Melting (SLM). In this process all overhanging structures above a certain angle require support structures. The ducts are designed with triangular cross-section to avoid support structures and a costly removal of these structures during post processing. The integrated valve in the channel of the dust blower needs support for the lever on the outside and at the internal gate. A downward tapering is added to lever and gate to reduce the amount of support to a linear support structure. The supports of the lever on the outside of the base can be removed easily. To remove the support structure of the internal valve gate, a shear edge has been integrated into the component as seen in figure 6. This allows the shearing of the support structure from the gate valve at the first full opening of the gate.

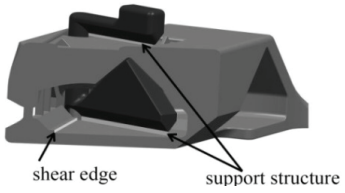

Fig. 6. Detail of the valve gate

After the design of the jigsaw base a prototype is produced in SLS and tested. A benchmark of the dust blower and extraction shows that over 95% of the sawdust on the work piece surface is removed by the optimized jigsaw base compared to the conventional base.

The design of the jigsaw base is driven by the optimal performance of the functions. The few process restrictions of additive manufacturing, like the need to support overhanging structures, are circumvented by design features like the triangular ducts. Currently design rules for various additive manufacturing processes are under development to assist designers in this task [16, 17]. A designer is strongly advised to comply with these rules to ensure a stable and cost efficient manufacturing process. The improved jigsaw is easy to manufacture additively and requires little post processing, but at the same time it is impossible to manufacture it conventionally.

The case of the jigsaw base clearly shows that the decision for a function driven design strategy was also a decision for additive manufacturing and against the option to change back to conventional manufacturing. The impact on the design of the product is considerable, because it allows a radical focus on the function, in the presented case on the optimal transportation of sawdust, and improves the performance of the product.

7. Conclusion

The continuous development of additive manufacturing processes keeps extending their capabilities and reduces manufacturing costs. Additive manufacturing becomes an established manufacturing process for serial products in a growing number of industrial sectors. Although it is unlikely to substitute conventional manufacturing in general, AM's unique characteristics are a valuable contribution to the portfolio of production technologies.

Currently the integration of additive manufacturing into industrial processes, on the shop floor as well as in product development, is only at the beginning. To help this process two strategies for product development are presented here. After identifying a component for additive manufacturing the designer has to choose between a manufacturing driven and a function driven design strategy. This is an important decision, because each path has benefits and disadvantages. In the manufacturing driven design strategy additive manufacturing is primarily used as a manufacturing technology with cost benefits at complex shapes and small lot sizes. This strategy requires a designer to comply with the design rules of conventional manufacturing. Once the situation of the product changes, e.g. the product is established in the market and sales increase, the production can easily be transferred to a different manufacturing process.

A function driven design strategy goes the opposite direction. The designer neglects all conventional design rules and designs the part only according to the functions of the component and the requirements of the AM process. The resulting design can only be produced by additive manufacturing and a change of production requires a major re-design. The benefits of this design strategy are a much better performance of the product in terms of weight, efficiency and the numbers of parts in the assembly. Both approaches were demonstrated by cases.

The chosen design strategy has also implications on the process to identify parts and components for additive manufacturing. In a manufacturing driven design strategy the performance of the product is independent of the manufacturing process. Therefore the business case of the selection process requires only cost and lead time estimations of the production processes. A business case for a function driven design has to take into account, that the shape and performance of the product will change a lot during the development process. This makes the upfront estimation of the production costs difficult and the improved performance might also create more revenue.

The awareness of the two very different design strategies for additive manufacturing will help the designer to make informed decisions on the route of the development process.

References

[1] Baldinger M, Duchi A. High Value Manufacturing. In: da Silva Bartolo PJ, editors. High Value Manufacturing: Advanced Research in Virtual and Rapid Prototyping: Proceedings of the 6th International Conference on Advanced Research in Virtual and Rapid Prototyping, p. 37–42.
[2] ASTM International, ISO. Terminology for Additive Manufacturing - Coordinate Systems and Test Methodologies (ISO/ASTM52921:2013).
[3] Gebhardt A. Understanding Additive Manufacturing - Rapid Prototyping - Rapid Tooling - Rapid Manufacturing. 1st ed. München: Hanser; 2011.
[4] Wohlers T, editor. Wohlers Report 2013 - Additive Manufacturing and 3D Printing State of the Industry - Annual Worldwide Progress Report. 18th ed. Fort Collins, CO: Wohlers Associates; 2013.
[5] Poprawe R. Lasertechnik für die Fertigung: Grundlagen, Perspektiven und Beispiele für den innovativen Ingenieur. Berlin: Springer; 2005.
[6] Caulfield B, McHugh PE, Lohfeld S. Dependence of mechanical properties of polyamide components on build parameters in the SLS process. J Mater Process Technol 2007;182:477–88.
[7] Spierings AB, Levy G, Labhart L, Wegener K. Production of functional parts using SLM - Opportunities and limitations. In: Bártolo PJ, editor. Proceedings of the 5th International Conference on Advanced Research in Virtual and Rapid Prototyping. London: Taylor & Francis; 2011, p. 785–790.
[8] Ahn S, Montero M, Odell D, Roundy S, Wright PK. Anisotropic material properties of fused deposition modeling ABS. Rapid Prototyping J 2002;8:248–57.
[9] Sood AK, Ohdar RK, Mahapatra SS. Parametric appraisal of mechanical property of fused deposition modelling processed parts. Mater. Des. 2010;31:287–95.
[10] Campbell T, Williams C, Ivanova O, Garrett B. Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing. Strategic Forsight Report 2011.
[11] Uglow B, Coe N, Vig RS, Wood A, Davies RJ. Capital Goods: 3D Printing: Don't Believe (All) The Hype; 2013.
[12] Gausemeier J, Echterhoff N, Wall M. Thinking ahead the Future of Additive Manufacturing: Innovation Roadmapping of Required Advancements. Paderborn; 2013.
[13] Leutenecker B, Lohmeyer Q, Meboldt M. Konstruieren mit generativen Fertigungsverfahren - Gestalterische Lösungen für die Substitution von Serienbauteilen. In: Krause D, Paetzhold K, Wartzack S, editors. Design for X: Beiträge zum 24. DfX-Symposium Oktober 2013. Hamburg: TuTech Innovation; 2013.
[14] Klahn C, Leutenecker B, Meboldt M. Design for Additive Manufacturing – Supporting the Substitution of Components in Series Products. Procedia CIRP 2014;21:138–43.
[15] Roland Berger Strategy Consultants. Additive manufacturing - A game changer for the manufacturing industry? Munich; 2013.
[16] Kranz J, Herzog D, Emmelmann C. Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4. J. Laser Appl. 2015;27:S14001.
[17] Adam GA, Zimmer D. Design for Additive Manufacturing—Element transitions and aggregated structures. CIRP J Manuf Sci Technol 2014;7:20–8.