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Investigations on a standardized process chain and support structure related rework procedures of SLM manufactured components

Berend Denkena[a], Marc-André Dittrich[a], Stefan Henning[a,*], Peter Lindecke[b]

[a]Institute of production engineering and machine tools (IFW), An der Universität 2, Garbsen 30823, Germany
[b]Fraunhofer-Einrichtung für Additive Produktionstechnologien (IAPT), Am Schleusengraben 14, 21029 Hamburg, Germany

Abstract

For the successful production of high quality parts by selective laser melting, various process steps are required. Besides the SLM process itself, different pre- and rework steps are needed to produce a final component. Therefore, the first part of this paper presents a concept of a standardized process chain for carrying out the necessary planning and production procedures. For this purpose, the CAD-model is enriched with information regarding support structures, the desired surface quality and the position of tooling points. Since major steps in the reworking procedure are the removal of residual powder, the removal of support structures and the finishing operations for functional component surfaces, selected experimental results concerning these steps are presented in the second part of the paper. Based on the result, recommendations for the design of support structures are given.

Keywords: Additive manufacturing, Machining, Process planning

1. Introduction and state of the art

The technology of additive manufacturing (AM) offers high potentials in the area of resource-efficient production of complex components, especially for expensive materials and small batch sizes. Furthermore, AM is particularly suitable for the production of topologically optimized lightweight components or for components with a high degree of functional integration [1], [2]. Due to the wide geometric design freedom, optimized lightweight structures can be produced with a weight saving of up to 80% [3]. The annually market growth of additive manufacturing has been more

* Corresponding author. Tel.: +49-511-7625751; fax: +49-511-7625115.
E-mail address: henning_s@ifw.uni-hannover.de

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than 20% in recent years [4]. Considering metal components, powder-bed-based processes, particularly selective laser melting (SLM), offer the highest potential [5].

However, there are some challenges to the mentioned benefits. First, the obtained surface roughness after SLM exceeds in many cases given tolerances. Second, the SLM process requires support structures to connect the component to the building platform and to prevent possible residual stress induced distortion during the building process [6]. Consequently, post-processing procedures are necessary. These procedures include for example unstitching from the building platform, removal of powder scraps in the support structures, removal of the support structures itself and machining of functional surfaces to achieve the desired surface qualities and dimensional accuracy [7]. The costs for all the post-processing steps can significantly exceed the costs of the actual additive production [8], [9]. To reduce the total manufacturing costs resulting from the different post-processing steps, an integrated and standardized process chain is required [10]. Due to the fundamentally different planning processes and technological boundary conditions in additive and metal-cutting production, the compatibility between the different planning steps is considered low [11]. Furthermore, the necessary information flows between the different process steps, from product design to quality assurance, are currently not defined [12]. In order to overcome these challenges, the first part of the article presents an approach of a standardized digital process chain. The second part gives a more detailed view on post-processing of the component's support structures. Here, the powder removability and the machinability are investigated. Based on the results, recommendations for the selection of suitable structure variants are given.

2. Concept for a standardized digital process chain

As mentioned above, the fundamental differences in planning of additive manufacturing processes and conventional machining processes require different software environments and, thus, different data types. This results in incompatibilities in the flow of information between the process steps. Figure 1 presents a concept for a standardized process chain including the definition of the generally needed information flows and interchanges during the component manufacturing. The process chain is divided into three main steps: First, the product development, where all activities concerning the component design and further steps, like the topology optimization, take place. Second, the AM process, which includes all necessary operations regarding the SLM process. Third, the finishing, which encompasses all conventional machining activities and quality assurance. In order to enable interactions between the mentioned steps, two closed feedback loops are defined. The inner feedback loop (shown in blue) returns information from the process planning of the additive manufacturing process to the design phase. This information includes for example geometric data on support structures and necessary stock allowances for the compensation of workpiece distortions caused by the AM process. The outer feedback loop (shown in red) handles for example information regarding the clamping of the workpiece in machining. Furthermore, guidelines from quality assurance are returned to the design phase. A central element of this concept is an enriched CAD-model, which acts as an information carrier. For this purpose, the information from the different planning steps are stored in the geometric features of the CAD-model. To ensure a maximum compatibility over different software systems that are used along the whole planning chain, the CAD-model is stored in the common STEP format. The information is stored as an attribute in terms of a string and defined in a lookup-table attached to the STEP-data. Since several interactions between the process steps exist, e.g. position changes of tooling points, or different stock allowances for different metal-cutting processes, several passes through this planning procedure may be necessary. An example of an enriched CAD-model is shown in Figure 1. In this example, geometry relevant information is stored and visualized by different surface colors after a first iteration through the inner information loop, where necessary support structure have been defined. The presented digital process chain allows planning of near-net-shape semi-finished products under consideration of the required post-processing steps. However, the successful implementation of the planning procedure requires technological knowledge, e.g. on the influence of the support structure design on their machinability, suitable positions for tooling points or the necessary stock allowance for machining operations. In the following, effects of the support structure design on the post processing operations powder removal and machining are presented.

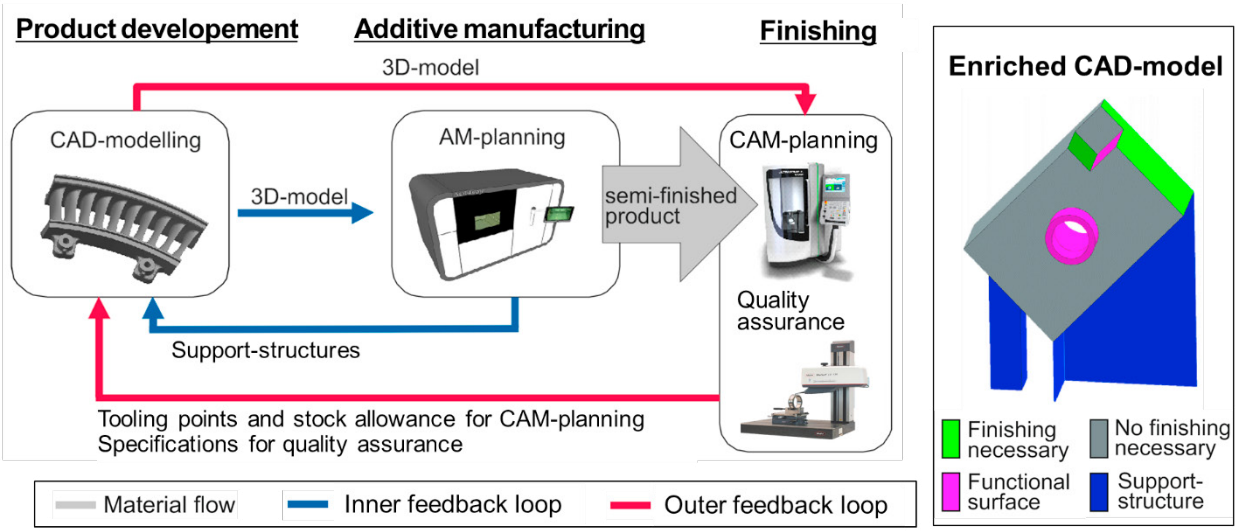

Figure 1: Concept for a standardized process chain based on an enriched CAD-model

3. Material usage and powder removability for TiAl6V4 support structures

Due to the delicate geometries of support structures, powder scraps last between these structure elements after the SLM process is finished. The residual powder leads to environmental contamination on the one hand. On the other hand, powder scraps can be molten up during the subsequent tempering process, which is generally carried out before the component is removed from the building platform. In this case, the molten powder scraps can connect to the component. Thus, the residual powder must be removed before the post-processing takes place. To understand the influence of different types of support geometries on the powder removability, the experimental procedure shown in Figure 2 was carried out.

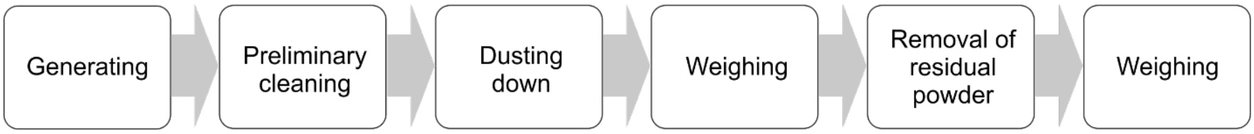

Figure 2: Procedure of material usage experiment

After the additive manufacturing process of the specimens, the majority of the powder was removed with a brush. Then the platform with the specimens was tilted into a vertical orientation. To remove more powder and simulate the standard platform-removal procedure, the platform was knocked off lightly with a plastic mallet fifteen times and then rotated 90° in the horizontal plane. Afterwards these steps of dusting down and rotating were repeated three times. Hereinafter, the specimens were removed from the platform and weighed one by one (weighing after test procedure). In the next step, the remaining powder was removed and the samples are weighed again. Finally, the mean weights of the specimen masses were compared to the mean values of reference samples. Subsequently, the removability of the inboard powder was evaluated and indicated by a powder removability factor (PRF), which was defined as the ratio of the calculated weights of the support structure and residual powder at the two measurement stages. A PRF of 1 indicates that all powder could be removed during the tapping procedure.

To evaluate the differences in powder removability, cubes of five different support geometry types were manufactured and handled according to the experimental procedure described above. These support structures were printed on a SLM Solutions 500HL machine with a layer thickness of 60 µm, a Laser Power of 80 W and a scanning velocity of 400 mm/s. The used powder was a spherical, gas atomized TiAl6V4 powder with an average particle size of 37.4 µm. Afterwards the supports were removed and the contact surfaces smoothened with a file. Then the mean value of the total weights of these parts was determined.

With the aim to detect differences of 1 g between the test series, the required sample size *n* was set to 5. The mean value for the total weight of the cube without support structures (see Figure 3) of 16.45 g was set as reference. The structures used for the material usage test series are shown in Figure 3 on the right hand side. The support geometry 1 is designed with fragmentation, which should enable a sufficient powder removability. The pen support variant 2 combines a higher bending stiffness with a good support and powder removability. Because of the H-profile of the outer struts of the geometry 3, detachment between them and the components ought to be avoided and the thicker beams of the perforation of this geometry have more stability. The geometry 4 consists of a very strongly perforated block support structure (beam width: 0.4 mm, angle: 60°, height: 1 mm, solid height: 3 mm). Also, conventional supports with standard support parameters (geometry 5) were investigated within the experiments (fragmentation: x-interval = y-interval = 2.5 mm, separation width = 0.2 mm; perforations beam = 0.6 mm, angle = 60°, height = 1.0 mm, solid height = 3.0 mm, separation width = 0.2 mm). The diagram on the left hand side of Figure 3 summarizes the calculated weights of the support structures. It can be seen that geometries 2 and 3 present the smallest differences in weight and therefore the lowest amount of residual powder located between the support structure elements. Consequently, taking into account only the powder removability, these two structure variants are recommended.

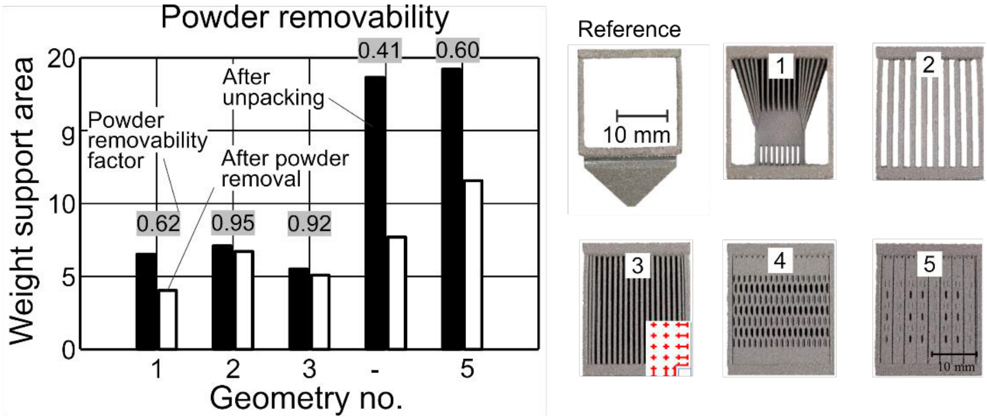

Figure 3: Weights of the support structures and powder removability factor

However, during the experiments it could be observed that the structures not only need to have a certain bending stiffness to withstand the forces of the re-coater, they also have to prevent warpage in the XY plane. Figure 4 illustrates exemplarily the effect at the upper corner of the geometries 2 and 4.

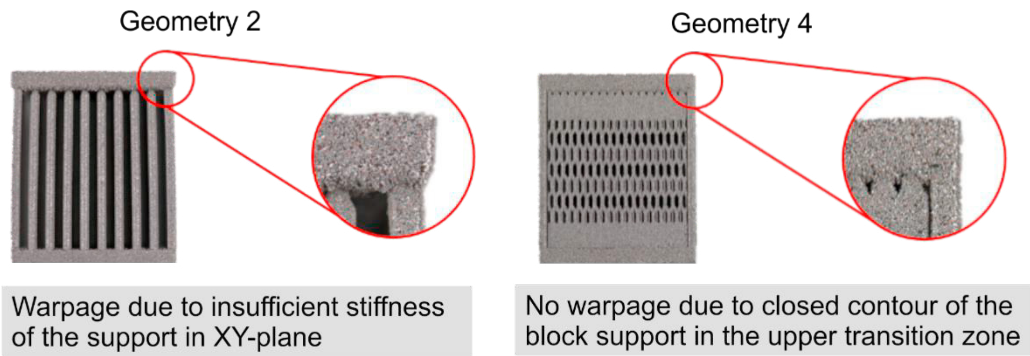

Figure 4: Defects due to insufficient bending stiffness of support structures

Based on the presented results, it can be derived that a high degree of perforation as well as a high degree of fragmentation is recommended to ensure that only a small amount of residual powder is left between the support structure elements after the SLM process. However, the warpage of the structure has to be considered, too. If the selected structure causes warpage in the upper transition zone, it is not suitable for the process with the selected material type, layer thickness and laser power. Taking this type of defect into account, it can be concluded that structure 3 is the most suitable compromise in terms of powder removability, weight and material consumption and stiffness in the bending zone for the investigated material.

4. Support structure removal by machine tool

A central element of a standardized process chain is an automated removal of support structures by a machine tool. However, support structures are mostly removed by hand currently. Thus, only little knowledge exists about process forces as well as surface qualities that can be achieved on functional surfaces. To gain further insight, four different support structure geometries from Inconel 718 were produced and machined. The investigated support structure variants are depicted in Figure 5. Based on the results presented in the chapter above, the structures were designed with different levels of fragmentation and perforation. Structure A has a high degree of perforation in the outer contour and bars inside the contour cage. Structure B has a similar high level of perforation on the outer cage, but consists of fragmented grid geometry in the cross section instead of bars. Structure C is very similar to structure A, but has less perforation in the outer contour. Structure D consists only of bars.

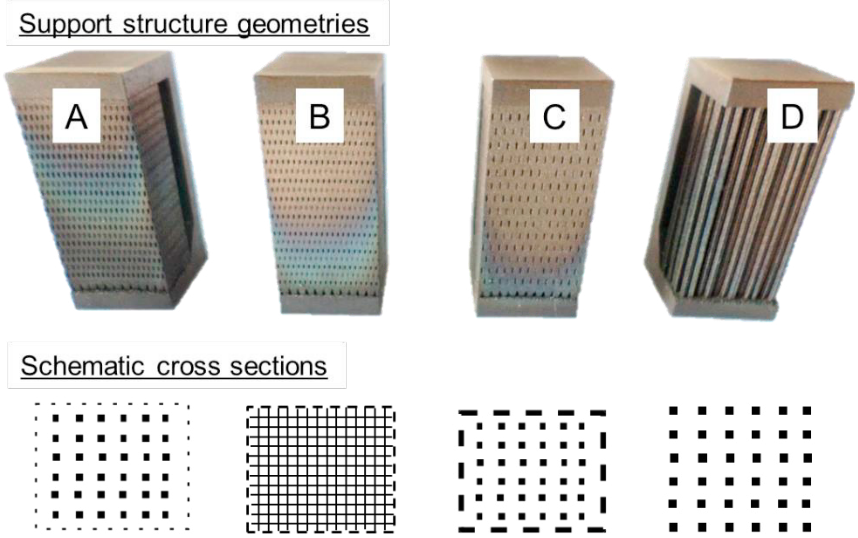

Figure 5: Support structures for machining experiments

Machining was carried out in two different ways. On the one hand, only support structures were machined. Here, general knowledge about the machinability in terms of the material separating behavior of the structures should be gained. In addition, the influence of the structure geometry on the process forces during removal was also investigated to consider resulting tool- and machine loads. On the other hand, the machining of these support structures was combined with the removal of a defined finishing allowance on the demonstration parts. Here, the achieved surface roughness was measured and evaluated. This should determine, whether the structure removal can be combined with a finishing operation for generating a functional surface in one joint cutting operation.

Both test series were performed on a Heller H5000 machine tool. The used cutting tool was a Kennametal F4AS1000ADL38 with a tooth count of 4 and a diameter of 10 mm. The experiments were carried out in a flank milling process with cooling lubricant. A cutting speed of 40 m/min and a cutting depth of 2 mm were used. The feed rate was varied in four steps between 0.025 and 0.1 mm. First, the results after machining the structures without integration of the finishing-cut are shown in Figure 6. Clear differences in general machinability can be identified. Geometry B, that consists of a fragmented grid cross section, shows best machinability. At geometries A and C, the inner bar structure is partially pushed away. Comparing these two variants, structure C displays a better machinability, due to a lower level of perforation. At geometry D, the bars are mainly torn out due to the feed movement of the tool.

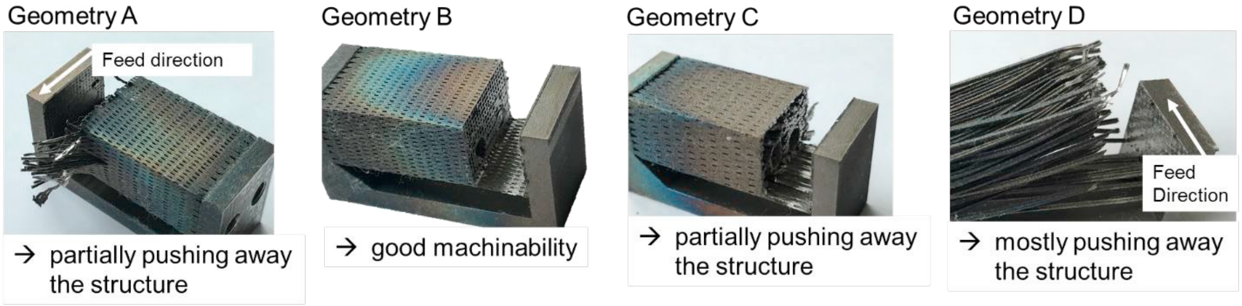

Figure 6: Machinability of support structures

In order to gain knowledge about the tool load during the process, the feed forces were measured during machining. The process forces were measured with a Kistler 9255C dynamometer. The average feed forces that occur during the removal of the structures are presented in Figure 7. It can be seen that the feed forces are lowest for structural geometries A and D. The highest forces can be observed in machining structure C. With the exception of structure D, the feed force increases with an increasing feed rate. An explanation for this observation can be seen in the different material separation mechanisms. While the material of the structures A to C is mainly cut, the material of structure D is mostly torn out.

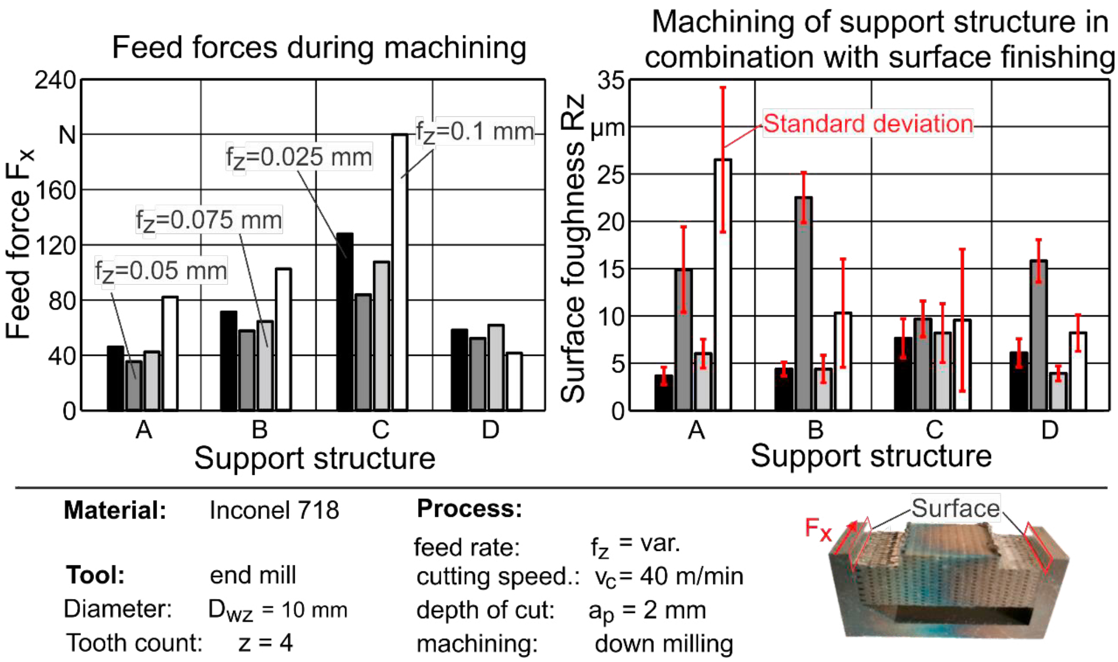

Figure 7: Measured feed force and surface roughness due to machining

In order to evaluate the possibility of combining the support structure removal with the surface finishing process in a joint machining operation, machining of the four structure variants was examined in combination with the removal of a finishing allowance at the transition zone, where the structure is connected to the component. The evaluation criterion here was the surface roughness achieved by the finishing cut (right hand part of Figure 7). It can be seen that the lowest roughness is obtained at a feed per tooth of 0.025 and 0.075 mm. Feeds of 0.05 and 0.1 mm lead to the highest roughness values. However, this effect cannot be traced back to the selected feed rate, but to existing dimensional fluctuations in the range of more than 0.5 mm on the flanks of the additive manufactured blanks, which lead to strong deviations from the desired finishing allowance.

Still, the results indicate that a combination of structure removal and finishing in a joint operation is not advisable. The removal of a defined finishing stock cannot be guaranteed due to the variations in stock allowance. Instead, an allowance of about 1 mm is recommended on functional surfaces, which is then reduced to a defined finishing allowance in an additional pre-finishing operation that can be combined with the support structure removal. In this way, machining with defined cutting depths can be ensured in the finishing operation that takes place afterwards. To sum up the gained findings, it can be said that support structure B offers the best compromise between machinability and process forces and is therefore recommended from a machining perspective.

5. Conclusion and Outlook

In this article, a new approach for a standardized process chain of additive manufacturing and subsequent machining was presented. First, a concept of a standardized process chain for carrying out the necessary planning and production procedures was introduced. For this purpose, the CAD-model is enriched with information regarding support structures, the desired surface quality and the position of tooling points. A holistic CAD-model that is enriched with the results of these different planning steps ensures the compatibility between the different software environments, that are used in planning additive manufacturing- and conventional machining processes.

Since major steps in the reworking procedure are the removal of residual powder, the removal of support structures and the finishing operations for functional component surfaces, results of experimental investigations of these aspects were highlighted in the second part of the article. Based on these investigations, it can be concluded that the selection of the best possible support structure should not only take into account the stability and process time during the SLM process itself, but also the influence that the structures have on the rework processing steps.

The findings presented in this paper have been obtained using simple analogy processes and components. In the near future, the transferability of these findings to a complex free-form component will be evaluated. Furthermore, research activities in the near future will focus on the development of mathematical algorithms to define suitable tooling points based on a geometrical analysis of the components shape. All necessary information about these tooling points will then be stored in the STEP based enriched CAD model.

6. Acknowledgements

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References

[1] A. Gebhardt: 3D-Drucken – Grundlagen und Anwendung des Additive Manufacturing (AM). Carl Hanser Verlag, München (2014).

[2] D. R. Eyers, A. T. Potter: Industrial Additive Manufacturing – A manufacturing systems perspective. Computers in Industry 92-93 (2017) pp. 208-218.

[3] C. Pickert, M. Wirth: Additive Fertigungsverfahren – Center for Digital Fabrication (CEDIFA). Report, Julius-Maximilians-Universität Würzburg, (2013).

[4] T. Wohlers: Wohlers Report 2014: 3D Printing and Additive Manufacturing State of the Industry – Annual Worldwide Progress Report. Wohlers Associates (2015).

[5] K. Satish Prakash, T. Nancharaih, V. V. Subba Rao: Additive Manufacturing Techniques in Manufacturing – An Overview. Materials Today: Proceedings 5 (2018), pp. 3873-3882.

[6] L. van Belle, G. Vansteenkiste, J.-C. Boyer: Investigation on residual stresses induced during the selective laser melting process. Transtech Publications Switzerland (2013).

[7] H. Krauss, J. Schilip, M. F. Zaeh: Reduktion der Oberflächenrauheit und oberflächennaher Fehlstellen bei Hochleistungs-SLM-Bauteilen. RapidTech (2013).

[8] R. Berger: Additive Manufacturing – Next generation. Study (2016).

[9] J.K. Watson, K.M.B. Taminger,: A decision-support model for selecting additive manufacturing versus subtractive manufacturing based on energy consumption. Journal of Cleaner Production 176 (2018), pp. 1316-1322.

[10] A. Elser, M. Königs, A. Verl, M. Servos: On achieving accuracy and efficiency in Additive Manufacturing: Requirements on a hybrid CAM system. Procedia CIRP 72 (2018), pp. 1512-1517.

[11] B.H. Jared et al.: Additive manufacturing: Toward holistic design. Scripta Materialia 135 (2017), pp. 141-147.

[12] S. Müller, E. Westkämper: Modelling of Production Processes A Theoretical Approach to Additive Manufacturing. Procedia CIRP 72 (2018), pp. 1524-1529.