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Considering Part Orientation in Design for Additive Manufacturing

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Abstract

Additive Manufacturing (AM) is established not only in prototyping, but also in serial production of end-use products. To use the full potential of the production technology the restrictions of current additive manufacturing processes (like support structures in Selective Laser Melting) must be considered in the design process. Especially the compliance with design rules from early design stages on is important in AM serial production, due to production quantities and the resulting scale effect. The part orientation in the build space has a strong influence on many quality characteristics. In order to use the full potential and to consider the restrictions from the start, a design guideline is necessary to support the whole design process.

For this purpose, this paper presents a framework for design guidelines. The framework distinguishes between process characteristics, design principles and design rules; each supporting the designer during different stages of the design process. Furthermore, the paper examines the influence of part orientation in existing design rules and elaborates its importance. Based on this result, the design principle "early determination of part orientation" is presented, which includes a process for determining the part orientation in early stage of the design process.

In addition, a design process for additive manufactured parts is demonstrated on an extensive showcase, following the guideline framework and including the principle for early determination of part orientation. The presented framework proved to be helpful in the design process and will be used in the future to collect more process characteristics, design principles and rules.

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Keywords: Part Orientation; Additive Manufacturing; Design Process; Design for Additive Manufacturing

1. Introduction

Additive Manufacturing (AM), or 3D printing - as it is referred to in the media, is a group of manufacturing technologies which produces three-dimensional objects by adding material, usually in a layer by layer process. In the beginning of the manufacturing technologies in the 1980th, the first applications were the production of prototypes. During the following decades the manufacturing technology and materials evolved and nowadays, new fields of application are possible.

Additive Manufacturing processes are technologically mature for industrial production and due to a sufficient process stability and a rising competition between service providers [1] Additive Manufacturing becomes economically feasible for a growing number of industrial and end-user applications [2]. Today there are many different Additive Manufacturing processes available, some of which are capable of serial direct part production. Nowadays, processes like Selective Laser Melting (SLM), Selective Laser Sintering (SLS) and, with some limitations, Fused Deposition Modeling (FDM) are used to produce end-user parts.

The possibility for serial direct part production brought new challenges for industries. To implement new production technologies, companies have to identify suitable parts for AM [3]. Furthermore, the new production process created new possibilities but also new restrictions to the design. Unlocking the design potential of AM is a big challenge, because of the tradition and fixed mind-sets of experienced designers and of course due to the lack of knowledge on the new technology [4,5].

Introducing a new way of thinking to designers can be achieved through design guidelines and training. In particular, it is difficult to obtain support for the designers in terms of design guidelines and design rules of AM. At the moment design rules are mostly presented in academic publications for an academic target audience. There is a challenge to develop a design guideline for AM which can be used in industry and is based on industrial experience.

2. Design Guideline

The knowledge needed for a good design for a specific application is complex and multi-facetted. The different publications of design rules for AM are usually driven scientifically [5] and follow a systematic scientific structure which doesn't necessarily match the workflow of practitioners.

To implement AM Design in the industry, a user-centered structure of the design guideline is necessary to assist the de-

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signer in product development and to overcome reservations against novel production methods. Therefore, the presented design guideline follows product development respectively design process.

A design process can be roughly divided into the stages of task clarification, conceptual design, embodiment design and final design [6,7]. The tasks in each of these stages require a different kind of guidelines to support designers. Based on the needs along the process, the design guideline is divided into three areas: *process characteristics*, *design principles* and *design rules*. These are not exclusively assigned to the individual stages but are rather aligned with the developer's needs.

The multitude of AM processes and materials makes the development of a generic design guideline for all feasible combinations of processes and materials an impossible task, if it is intended to have any practical use [5]. Therefore, the presented design guidelines primarily focus on AM processes for the production of end-user parts, especially on SLS, SLM and FDM. The presented process characteristics, design principles and design rules can be applied to individual processes or even to Additive Manufacturing in general. For reasons of simplicity, this publication focuses primarily on SLM processes.

2.1. Process Characteristics

The process characteristics summarize the basic knowledge on the working principle of a process for the design and should be known to the designer if he wants to design AM components. They describe the characteristics conditioned by the process which have an impact on the design, and, therefore, must be taken into account for the design of AM components. They illustrate the specifics of the process. Thus, for example, the stair-step effect is explained and the need for support structures. The basics on process features of different AM technologies are already available in the literature and can be derived respectively prepared therefrom [2,8].

2.2. Design Principles

Design principles support the designer to transfer a principle solution into a specific, manufacturable design. They enable the developer to exploit AM's freedom of design and to circumvent existing AM constraints creatively. The design principles can range from simple notes to cut costs to recommendations which largely impact the design of parts. They also give instructions to increase part quality or to reduce manufacturing costs respectively post processing effort.

Like in design principles for conventional manufacturing a trade-off between conflicting principles may be needed [9]. In such a case, the designer has to rate the impact and decide which principle is more important to the overall objective of the design.

Design principles are rarely found in literature as they are often based on experiences of developers. There are a few case studies on good AM designs, but those usually don't provide enough background information to extract and refine the experience of the designer from the part design.

2.3. Design Rules

The design rules cover the necessary characteristic facts and figures for designers to design manufacturable components for the AM process. These design rules depend on the chosen manufacturing process, material, machine and machine parameters. Initial reference values for designing parts can be taken from the literature. However for a specific design the characteristic values of the chosen production system are necessary and a communication with the workshop is essential. The design rules includes such values as minimum wall thickness or roughness information which depend on the machine and process parameters.

3. Part Orientation

Part orientation describes the rotation of the part in the build space around the axes of the machine's coordinate system [10]. The term excludes a translation of the part along the coordinate axes of the machine's coordinate system during part positioning [10].

3.1. Significance of Part Orientation for Design

Based on the layer by layer manufacturing process there is a difference between the part geometry in building direction (typically the z-direction of the machine's coordinate system) and the geometry orthogonal to the building direction. The orthogonal shape is produced almost continuous while the part production in build direction is discontinuous in discrete steps of one layer thickness. Furthermore some AM processes require support structures in build direction and the design has influence on the component warping. Therefore the impact of part orientation on the design of the part is significant.

The importance of part orientation is reflected in an analysis of already published design rules. Adam published a design rule catalog to support suitable designs for AM with 55 design rules [11]. The design rules are developed for SLS, FDM and SLM based on a process independent method for developing design rules for AM [12].

In preparation of this contribution we analyzed and classified the design rules of Adam for direct, indirect or no dependence of the part orientation. Design rules with direct request for orientation are added to the direct dependence design rules. The design rules which need a specific orientation to be applicable are classified as indirect dependence design rules. For example the rule on inner radius in simple curved elements provides no instruction how to orientate the inner radius, but it states the minimal radius to build up horizontal holes without support structure in SLM an FDM. Strictly speaking, this is no direct instruction to orientate the element but a dependence on the orientation is clearly stated. Therefore this rule is added to the indirect dependent design rules.

The design rule analysis of Selective Laser Sintering (SLS) shows that over 55% are direct or indirect dependent on the orientation. For SLM and FDM 70% of the design rules depend on part orientation, see Fig. 1.

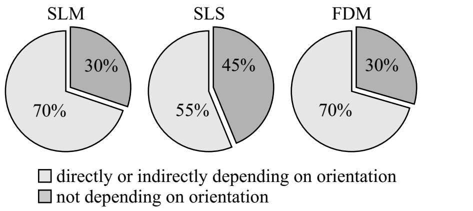

Fig. 1. Analysis results of design rule dependencies on part orientation

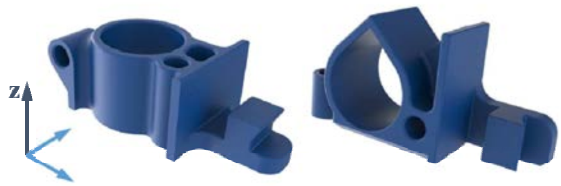

Fig. 2. Impact of part orientation on the final design

3.2. Quality Features for Part Orientation

There is a variety of studies on the optimization of the part orientation in Additive Manufacturing. The first ones were carried out in the early stages of the technology in the 1990s years. In particular, for Stereolithography (SLA) there are a variety of publications [13,14]. Research [15–18] deals usually with existing part designs to be oriented in build space. The component orientation is set on the basis of different quality features. These quality features are dimensional accuracy, surface quality, shape accuracy, building costs, building time, component warping, stability, support volume, utilization of building space, effort of post processing and accessibility of support structures [15].

The quality features listed here are all directly dependent on the geometry of the part. In common orientation strategies the part (after the final design) is rotated along the part's coordinate axes to achieve an optimum of the quality features [19]. The result of such a multi-objective optimization is a compromise to balance the different quality features.

3.3. Design Principle: Early Determination of Part Orientation

This previous work demonstrates the importance of the orientation in the build space for the quality of the produced part. Nevertheless the work was limited on orienting a given final part design. We propose a new principle to determine the orientation at an early stage of the design process. The early determination the orientation before the final design allows changes to the shape to improve the quality characteristics.

The design principle *early determination of the part orientation* states that the orientation should be determined before the final design of the part begins. This allows the designer to base his design on this decision and bypass or avoid certain process restrictions by an appropriate design.

This principle has a high impact on the part design. This is especially true for AM processes like SLM because of the necessary support structure, component warping and orientation depending surface quality. The high number of orientation depending design rules highlights this. The impact of the early orientation and application of common design rules is illustrated by a simple part with same functions and two different orientations in Fig. 2.

The challenge here is the determination of part orientation despite an uncertainty due to the early stage of design process.

3.4. Process to Determine the Part Orientation

To assist the designer with the challenge of an early determination of the part orientation, the procedure depicted in Fig. 3 was developed. It is based on dividing the concept design of the part into several design elements and analyzing these separately. In this analysis the orientation's effects on the quality features of the elements are evaluated. Subsequently the relevance of each element to the part function is rated to quantify the impact of part orientation. The orientation of the part is determined based on this rating.

In the first step of the process depicted in Fig. 3 the concept of the part is decomposed into design elements. Here a design element is an individual or a meaningful combination of active surfaces designated to fulfill a function in the component. An example of a design element is a thread with a clamping surface or the contact surfaces of an attachment.

The next step assesses whether a particular orientation of the design element has a significant influence on the quality feature. If not, the design element can be neglected in the orientation of the part. If the element has an influence, then the designer must determine the optimal positioning of the design element for the quality feature. This can cause orientation conflicts between the different quality characteristics, e.g. one orientation results in a better surface roughness while the other reduces the risk of warping. Here, the designer has to specify which quality feature should be given higher priority and therefore determines the orientation of the design element. In our experience a review of all quality features for each design element is highly time-consuming and often unnecessary. A reduction of scope to quality features with a high impact in the early design phase is quite useful to reduce the workload.

We analyzed the orientation processes of about twenty parts to identify necessary quality features. Based on this analysis we reduced the quality features to the following relevant ones: surface quality, dimensional stability, component distortion, support structure and building height. This set of quality features allows determining the part orientation in an early design phase when no detailed part design is available.

Based on best individual orientations of each element the overall part orientation is determined. The design elements are weighted according to their importance for the function of the component. It is likely that additional effort in post-processing is needed when the design element is not positioned according to its optimum orientation. Furthermore, the number of design elements lying in a similar orientation is important here, since the effort of post-processing can increase significantly if their orientation is not taken into account. The designer has to

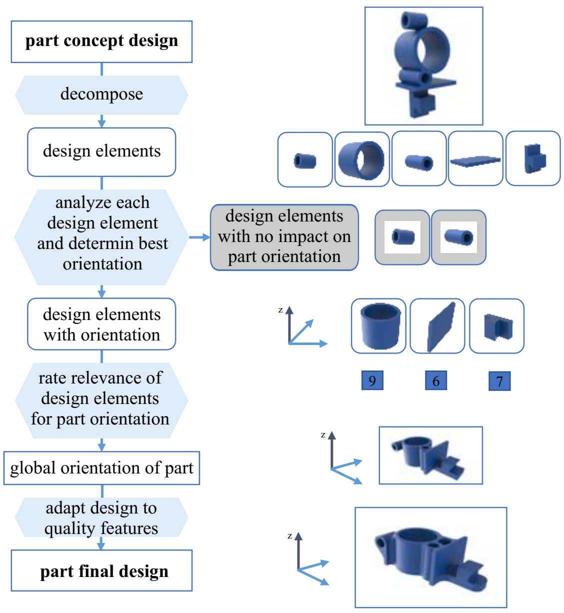

Fig. 3. Process for defining part orientation in early design stage

consider in this step the entire part design also and whether an adjustment of the orientation is possible by a redesign of individual design elements.

4. Application to Design Process and Case Study

The design process of components for Additive Manufacturing is no different from the basic design process for conventional components as documented in VDI 2221 [7]. The designer rather has to pay attention to the process-specific design principles. In particular, the design principles of function-oriented design and the early determination of the part orientation have great influence on the result of the design process.

4.1. Application in the Design Process

The developer must of course know the process characteristics of Additive Manufacturing before he enters the design process. In the first, task clarification phase of design process, there is no difference to conventional design.

In the second, conceptual design phase, during the determination of functions and development of a principal solution there is also no difference. However, it should be noted that it has been shown in many cases that a very strict applied function abstraction away from the component geometry is useful. This abstraction makes it easier for the designer to leave existing, conventional manufacturing constraints and enable him to develop principle solutions, which use the design advantage of Additive Manufacturing. In this phase of the design process, it is necessary to know about the design principles of AM to ensure a good and adapted product design. After the second phase there is a principal solution which fulfills all the specifications. We refer to this principal solution or design concept as *ideal-design*, because it is an ideal solution for all functions which fulfills the specifications without any restrictions of a manufacturing process.

In the third, the conceptual design phase, the ideal-design is transferred into a *feasible-design*, which is producible by AM and following post-processing. In this phase the design principles become very important, because they support the designer in the transfer and help to reduce cost and enhance quality. The principle of early determination of the part orientation achieves this by minimizing the limitations and restrictions of the production process like support structure or component distortion. Therefore, the ideal design can be divided into design elements and the build orientation is determined on this basis using the process presented here.

In the fourth, the final design phase, the feasible-design is prepared. This step is supported by the design rules for AM with characteristic variables for design elements.

4.2. Case Study

To illustrate the described design process and in particular the procedure for part orientation a case study is presented below. It involves a so-called laser cutting head of a laser cutter. The laser cutter is used to cut or engrave panels of organic materials such as wood (medium-density fiberboard) or acrylic with a CO_2 Laser. The laser cutting head is guided on a movable axis and has the function to hold the deflection mirror and the focus lens. The bottom of the lens is purged by compressed air to prevent contamination due to the resulting sublimation dust. The goal of the redesign of the laser cutting head is to improve the cleaning effect on the bottom of the lens by optimizing the air outlet [20]. In addition a compressed air cleaning of the top of the lens and the deflection mirror was implemented. The lens holder is to be produced by SLM in AlSi12.

At the beginning of the design process, the environment and the design space are set. For this all the interfaces of the system laser cutting head and the predetermined functional areas are specified in the CAD-model depicted in Fig. 4a.

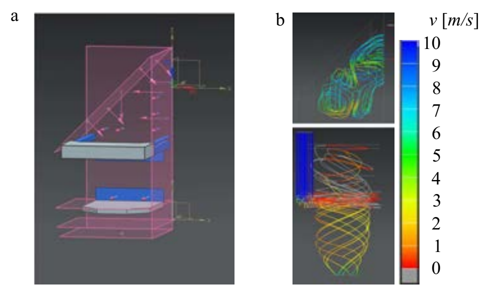

Fig. 4. Fix arrangements (a) flow simulation for compressed air flush (b)

Subsequently, solutions have been developed for the optimized cleaning of the mirror and of the lens using CFD. The results of the optimization are shown in Fig. 4b. The results from the simulation and function areas of the air duct for cleaning have been included in the CAD model. For a better view, and thus improved division into shape elements all functional surfaces were coated with a material thickness of 1 mm, resulting in the ideal-design of the laser cutting head in Fig. 5.

Here, the design principle of function-oriented design has been taken into account. In the further procedure, the part is

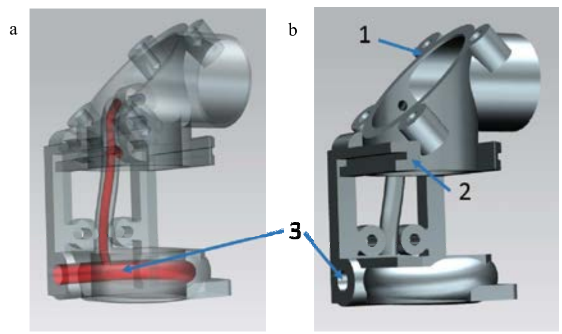

Fig. 5. Ideal-design of internal (a) and external (b) geometry elements

oriented by applying the design principle early determination of the part orientation. It begins with the dismantling into design elements. Subsequently the design elements are analyzed and the orientation is determined.

To illustrate the process presented here three design elements of the laser cutting head are exemplarily discussed.

- The first group of elements is the mirror mounting surface with the threads of screws, Fig. 5b No. 1. A sufficient surface quality and dimensional accuracy is required to position the mirror correctly. The SLM process is not able to meet the requirements of both quality features despite optimal positioning. Therefore, post-processing of the mounting surface and threads is necessary. This will also remove any support structure if it is not already omitted by a suitable positioning. The building height is irrelevant due to the almost cubic body proportions relative to the total component. In summary the necessary post processing of the design elements makes the orientation of this group no longer relevant for part orientation.
- The second group of elements are the guide rails for the lens element, Fig. 5b No. 2. The achievable surface quality is sufficient for fulfilling the functions. The dimensional stability is in all orientations also sufficient. The possible component distortion of this design element is the limit, therefore is an orientation parallel to the build direction is preferred. In this orientation support structures are avoided at the rails. Since the removal of support structures from the guide rails is very tedious, this has a high priority on the orientation. The building height is negligible in relation to the overall size of the part.
- The third and last design element discussed in this example is the channel for the air, Fig. 5 No. 3. Both surface quality and dimensional accuracy are sufficient for the channel's function. Due to its small diameter between 1-5 mm internal support structures are not required. Through the integration of the channel in the component distortion and component height are irrelevant. Therefore the layout element is not relevant to the component orientation.

In summary the design elements of the guide rails of the lens frame and the high demands on the design element of the mounting surface and the positioning- and screw holes are decisive for the orientation of the part in the build chamber. The consideration of the overall component in respect of component distortion and part height reinforce the decision to orientate the laser cutting head in lying position with parallel to the building direction orientated guide rails for the lens holder. Since a thread needs to be cut on the lens-side beam path, the removal of the necessary support structure is negligible. The beam path at the entrance on the other hand does not have to be reworked and has a certain flexibility in the design. Therefore, the support structures in the beam entrance can be avoided by an adjustment of its shape.

Finally some minor adjustments are done to avoid supporting structures and to follow all the design rules for the process and the material to meet specifications, creating the feasible-design of the laser cutting head.

In Fig. 6a, the feasible design is shown on the produced laser cutting head with all attachments during action in Fig. 6b.

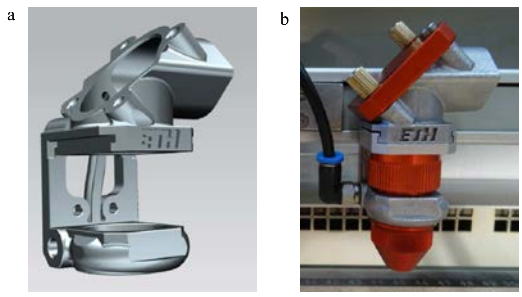

Fig. 6. Feasible-design (a) and additive manufactured part with assembled components (b)

5. Conclusion

The continuous development of AM increases the application fields for these technologies. In particular, advances in the areas of materials, part quality, process stability and reduced manufacturing costs extended the use of AM from prototyping to the production of end-use parts in series production.

To a designer the very different characteristics of processes and parts are a major challenge in unlocking the design potential of AM. To address this current lack of experience and implement design knowledge in industry, a user-centered design guideline for designers is developed. It consists of process characteristics, design principles and design rules to support the designer in the design phase of conceptual design, embodiment design and final design.

One of these design principles is presented here. The principle of the early determination of the part orientation is of high relevance particularly in the construction of SLM parts. Therefore, an approach was presented to determine the part orientation in the early stage of the design based on the ideal-design. In this approach, the part is decomposed in design elements which are analyzed. This enables early determination of part orientation and thus sets the basis for the transfer of the ideal-designs into a feasible design.

The presented design guideline will provide a proper guidance for designers to use the design advantage of Additive Manufacturing for serial products. The awareness for defining the part orientation in an early design stage will help to avoid design iterations and post processing.

The presented framework of process characteristics, design principles, design guidelines will be used in future works to provide the necessary design knowledge in a structured way. Further steps are a quantitative validation and the development of additional principles. The framework is applicable to other AM technologies and can be extended beyond the processes of FDM, SLS and SLM.

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