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Integrated Additive Product Development for Multi-Material Parts

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Abstract

Current resource and energy requirements call for the use of most beneficial materials with suitable design at the right place as well as appropriate manufacturing technologies and associated process chains. Additive manufacturing (AM) can play a key role for prospective multi-material components, particular with its versatile advantages in design-driven flexibility, customization, and lightweight design. However, obstacles to industrialization are less due to the technology itself rather than to the actual process chain integration, from conception to production and testing.

Accordingly, this contribution discusses an application example and arising problems with the integration of AM in product development. The authors highlight the most demanding steps of tailored constructive development methods, efficient manufacturing, post-processing and finishing as well as quality and lifetime management by continuous non-destructive testing.

Keywords: additive manufacturing; integrated product development; process chain integration; multi-material design; efficiency

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1. Introduction

Current efforts in product and production engineering show strong tendencies towards the continuously increasing integration of Additive Manufacturing (AM) technologies in product development and creation—offering huge potentials not only technically, but also accompanied by the shifting attention towards sustainable thinking (e.g., resource efficiency by customized solutions) [1]. Strengths and weaknesses, however, both lie in the basic process principle, which features a layer-based part generation, and thus permits an enormous design flexibility due to (not merely geometrically) manifold optimization strategies already within the early development phase. Despite this revolutionary process being steadily employed, the verification and validation of results still lack in reliability as a result of its diverse procedural influences, such as heat transfer induced warping of structures and geometric inconsistencies. Moreover, the unpredictability of tolerance satisfaction, going along with geometric complexity, promotes insecurities regarding the fulfillment of functional and aesthetic design requirements, particularly on the basis of difficult or even impossible high-precision post-processing that would have to be applied mandatorily. By taking these issues into account, the herein presented approach regarding an integrated additive product development focuses on a holistic strategy on the development procedure of multi-material and multiple processing components that incorporate additive manufacturing stages. In doing so, a simultaneous consideration of design and process-specific influences as well as highly precise post-processing technologies, like electrochemical machining (ECM), and characterization and validation activities based on non-destructive testing (NDT) operations is brought into focus. Furthermore, by visualizing all of this, the different stages are depicted using an application example comprising AM and fiber-reinforced elements by means of integral multi-material components.

2. State of the Art in Literature

In order to provide a quick overview of relevant scientific contributions within the individual stages stated above, this chapter gives a brief introduction into the state of the art in literature concerning constructional and technological engineering aspects in the context of AM from theoretical conceptualization to final verification.

2.1. Additive Manufacturing – A Design Point of View

Today, products are characterized by a rising number of different materials that constitute a product or system as a whole, each satisfying different properties (e.g., regarding mechanical, electrochemical or even aesthetical aspects). Nevertheless, the use of various suitable materials in one assembly is equally driven by economic requirements that need to be fulfilled in order to satisfy both customer and business demands. In the context of additive manufacturing, there is an even more acute demand for the most beneficial choice of material and geometric design, enabled by the highly innovative technologies incorporated in the extensive AM environment.

Due to manifold interrelations between conceptual design, material selection, and process definition, integrated and simultaneous engineering approaches receive a growing importance promoting a parallelization of tasks and direct coupling of development activities [2], which finally leads to a simultaneous definition of product (incorporating planning and development phase) and production, e.g. presented by Gausemeier et al. [3]. Further concepts consider the concurrent or integrated selection of suitable materials, which is a crucial step during product development (potentially already in the early phase). Accordingly, Ashby et al. [4] promote an initial assessment of materials also with regard to the immense interrelation of materials and technologies available for its processing, originating from two-dimensional property charts visualizing potential benefits and deficiencies of various materials (or processes) to facilitate a more profound selection and dismissal. Proceeding even further, Kaspar et al. [5] present a geometry-dependent and cross-component approach towards an integrated definition and selection of materials, processes, and joining technologies regarding a multi-criterial decision-making of technical, economic and ecological aspects.

Apart from material and process selection, AM technologies impose strict requirements on component design, not only because of the promising layer-based generative process, but also because of the sheer degree of freedom that can be achieved using, e.g., powder-based AM processes, such as electron beam melting (EBM), laser beam melting (LBM), and laser-based metal deposition (LBMD). In this context, Design for Additive Manufacturing (DfAM) approaches focus on the integration of process specific peculiarities, such as build direction and planar build orientation [6-8], feasible element sizes considering embossed and lofty features [9], surface patterning and quality [10] as well as mechanical properties resulting from varying process parameters and geometric embodiment [8]. The strict concentration on these aspects facilitate a design and preprocessing of additively manufactured components by early adoption of downstream process requirements. Regarding material efficient and lightweight-oriented design, numerous contributions treating the aforementioned optimization strategies as well as "constructal theory" have been published [11]. Paying attention to a most crucial aspect of AM – support structures and their influence on part performance and process stability – several contributions focus on support-free topology optimization of AM components [12]. By contrast, aspects regarding considerations on non-destructive testing and evaluation as well as design for lean precision post-processing, already within the early AM-oriented design stage, are rather subordinately or even not at all treated. Concerning these activities as an indispensable necessity for integrating AM in the process chain, approaches of AM-oriented Design for Testability are missing, as well as a precisely targeted assessment of design strategies for efficient and effective post-processing requirements.

2.2. Additive Manufacturing – A Technological Point of View

According to the standard SS-EN ISO 17296-2:2016, the general principles of additive manufacturing are listed in seven basic process categories and their feedstock materials, such as powder, wire, or sheets [13]. In metal-based processes, these materials are melted by energy sources like laser, electron beam, or electric arc [14]. In dependence of these categories and appropriate manufacturing processes as well as their limitations, the achievable design complexity is set, which is feasible within product development process. In many industries, an extensive use of additive manufacturing is still hampered due to an inconsistent quality. Common defects and/or deficits are, e.g., loss of alloying elements, high surface roughness, texture, porosity, lack of fusion, cracks, residual stresses, and distortion [14,15]. Thus, there is an intended demand of different post-processing operations to be conducted right after an initial post-processing step (depending on which technology was applied) is done in the form of separating the material component from building plate and support structures as well as its basic removal of powder. Depending on the material to be used, subsequently a heat treatment or hot isostatic pressing (HIP) needs to be performed to address the above-mentioned residual stresses [16]. Additionally, the relatively poor and step-like surface quality of layer-by-layer produced AM-parts necessitates particular attention being mainly influenced by, e.g., the alloy type, powder shape and size, layer thickness, morphology, and energy beam focal spot [14,17], particularly in tilted areas where partially melted powder particles agglomerate the surface.

Another important factor is represented by the dimensional accuracy, as shown in Table 1. To ensure the required tolerances in terms of functional aspects in dimension and shape (partly also with regard to surface quality, see section 3.1.3), the generated parts should be machined or even need a precision machining step. For this purpose, most often the well-known and long-established machining technologies of milling, turning and grinding are used for post-processing of (powder-based) AM parts. Since these technologies are regularly used for conventionally produced materials (e.g., casted, forged metals) a lot of research now focusses on the comparison of the machining of conventional and additive manufactured parts. In doing so, [17,18] report that cutting forces are increased for selective laser melted parts compared to wrought or casted materials. Moreover, the surface integrity after the machining step is analyzed, e.g., by [19,20]. The achievable roughness is similar for all samples no matter how they were produced. Other investigated parameters related to the surface integrity are, e.g., hardness, residual stresses, and subsurface microstructure [17,19,20]. However, the performance of the at least equivalent or even more precisely (comparable values to grinding or lapping [21]) unconventional post-processing technology of electrochemical machining (ECM) is not sufficiently investigated yet but, however, bears major potential for future solutions. A rare example of ECM used as post-processing shows Liu et al in [22], where the correction of shape and dimensions of a turbine blade tip is investigated, which was repaired by LBMD and finally using ECM.

Non-destructive testing (NDT) provides tools to control these quality issues in addition to a number of other quality assurance procedures during the whole lifecycle originating from the examination of the raw material (e.g., metal powder) via process control and after production inspection through to condition monitoring during operation [23]. The kind of NDT method most suitable for monitoring or inspection depends on defect type, process technology, geometry, and material or material combination, respectively. Systems for online monitoring are common in recent AM machines. Thus, besides tracking the process parameters, the monitoring of the AM process is implemented, for example, by optical systems working in the visible or infrared wave range and ultrasonic devices [15]. Online monitoring enables a direct correction of the defects or, if not possible, a termination of the process, hence, reducing production costs. The huge design freedom given by AM represents an issue concerning the usage of most NDT methods for inspection as critical areas might not or just partly be accessible, why most often computed tomography is used to check quality of critical parts. However, this kind of method is cost and time-consuming and not suitable for in-service inspections in many cases. Alternative approaches for the assessment of parts with complex geometry are, e.g., the volume POD tool [24], the impedance based structural monitoring [25] as well as the integration of sensors in the parts during the AM process [26]. The latter is mainly limited due to high process temperatures and typically requires a multi-step AM process. Furthermore, all these approaches require suitable quality management concepts to be developed and considered in the early stage of product development.

To summarize, various AM processes have been developed to manufacture parts with complex internal features and external contours and, moreover, work with alloys that are difficult to cast and process thermo-mechanically on the one hand, and on the other hand challenging to machine or build successfully by powder sintering in terms of quality assurance [14]. In the following, the well-established powder-bed-fusion (selective laser melting (SLM), refer to [27]) and direct energy deposition (laser-based metal deposition (LBMD), refer to [27]) processes are focused from a holistic perspective within an integrated additive product development framework applied on integral multi-material components.

3. Integrated Additive Product Development Framework

As stated above, the consideration of many multi-disciplinary but interrelated aspects is needed from the very beginning, when developing AM components. Therefore, a systematically integrated additive product development framework is required (see Fig. 1) to help experienced and inexperienced engineers deal with all the aspects of design, manufacturing, post-processing, and quality management inherently already within the early conception stage of product development. Thus, designing restrictions or adjustments with regard to an eventual capability of post-processing, quality inspection, and recyclability are prematurely taking into account.

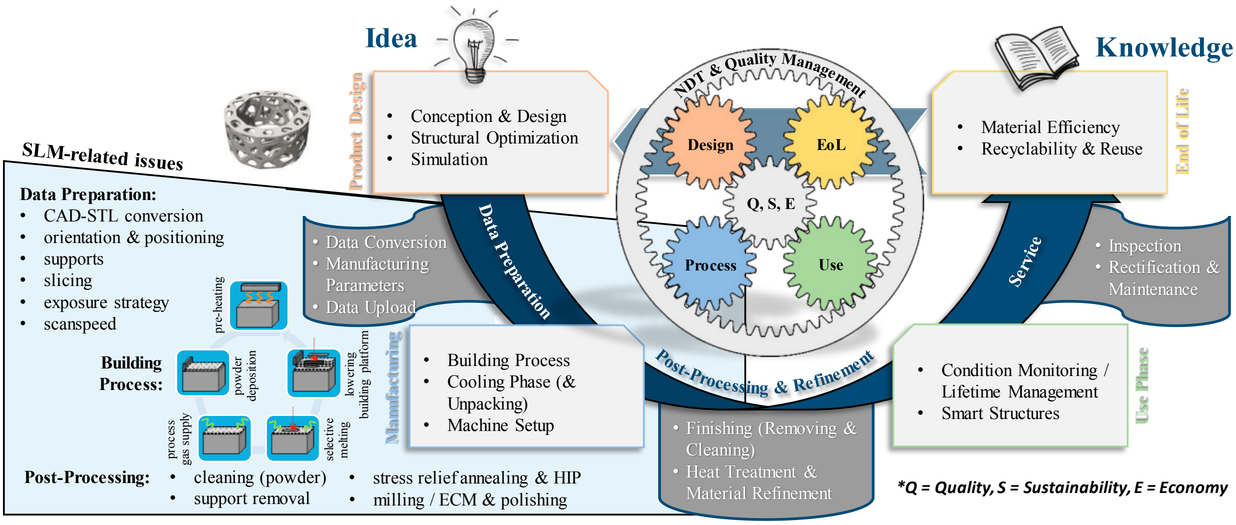

Fig. 1. Integrated additive product development framework

Accordingly, dealing with all the interlinked aspects along the product lifecycle beginning with the idea to implement AM within the actual product creation, up to the final storage of knowledge (experience and expertise) acquired throughout the whole development process for future projects, a successful integration of AM within the process chain of integral multi-material components can be realized.

To ensure more transparency within the theoretical approach, a visualized application example (e.g., from turbo machinery) is chosen to highlight the individual steps directly within the bounds of the complex topic, see Fig. 2.

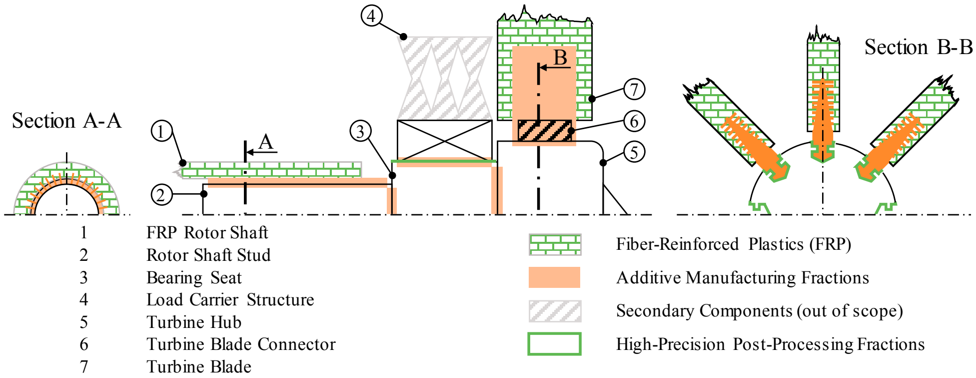

Fig. 2. Example of potential applications and joint sections regarding the integrated additive product development for multi-material parts

As shown in Fig. 2, the depicted rotor propeller shaft offers several sections to reconsider the actual design with regard to the revolutionary application of AM and its potentials, but also challenges within an integral multi-material system dimensioning. In doing so, large AM parts are rarely suitable by means of economic and technical aspects due to a limited building space and high production costs per volume or weight, respectively. Therefore, larger devices need to be assembled using multiple components, where the material and production method can be adjusted to the local demands. For example, the turbine hub (5) and turbine blade (7) necessitate a connection (6), which ideally follows the rules of lightweight design (keyword: rotary mass) on the one hand, and on the other hand still has to provide a stiff and robust joint as a whole but also with respect to both connecting surfaces. Thus, a specific joint section design has to be defined, which also comes along with all the complex considerations of processing and quality management. This aspect particularly involves the consideration of potentially beneficial process combinations, property-optimized choice of raw materials or semi-finished products as well as implications emerging from the aforementioned necessities regarding verification and testability of products.

To deal with all these considerations and its implications in the specific stages, the following sections go into further detail descriptively by means of different sections of the application example. Thus, the herein presented concept aims to extending established AM design approaches by post-processing, testing, and monitoring-oriented components, since design for manufacturability alone is not sufficient to accomplish a state of multilateral requirement satisfaction. In these multi-material structures, however, the internal interfaces always represent a potential breaking point due to a gradient in material properties, but also bear potential for misalignment of adjoining elements. These inadequacies stringently require thoroughly conducted engineering throughout the whole development process, considering any tasks from design and process definition up to ensuring service and maintenance operability during operation.

3.1. The Design Stage

The design stage is characterized by several conceptual as well as technological influences, determining promising use cases and success of different approaches. Therefore, an initial requirement specification needs to be applied mandatorily in order to work out benefits of the implementation of the process via, e.g., potential, function and manufacturability analyses. All those tasks need to be performed interlinked—regarding component, material and process chain capabilities.

In a first step, the component of interest needs to be screened regarding functional (e.g., need for bearings and flange geometries) and technological (e.g., surface hardening and resilience) requirements, in order to determine potential geometrical features that allow for the distinction of suitable process chain elements. Regarding the application example, this step shows potential for AM technologies to be used on element 2 (rotor shaft stud), as shown in Fig. 2. Second, suitable materials and production processes need to be determined that fulfill both component-specific, as well as process-related requirements. This step is influenced to a very high degree by the desired component behavior during service and the potentially available process spectrum and capabilities. These aspects consider, e.g., component loadability, machine type, build space, and accuracy. The third step consists of component embodiment design, where domain-specific design guidelines can be applied accordingly [7,9]. Furthermore, the embodiment has to incorporate additional objectives regarding the application of high-precision machining in post-processing, but also a verification and characterization-compatible design for using NDT techniques. Geometrical complexity as well as material-specific applicability of processes needs to be paid attention to for taking into account sensor and actuator positioning, sensing strategy, and achievable sensitivity [25]. Referring to the application example, this aspect is of major importance, if multi-material components are involved, here specifically regarding pinned surface interfaces and its occurring damages (elements 1-2 and 6-7) as well as potential delamination within FRP components (e.g., elements 1 and 7).

3.2. The Manufacturing Stage

According to respective process principles, boundary conditions like space, available materials as well as complexity are specified by the manufacturing system. The selection of the manufacturing process chain directly interacts with upstream and downstream development activities, which have to be adapted according to the properties to be achieved, e.g., with regard to accuracy, thermal distortion, or roughness (see Table 1).

Table 1: Comparison of process performance of PBF and DED referring to [14,28,29]: insufficient, low = ● – ●●●●● = good/high

Properties / Process	Powder Bed Fusion (PBF)		Direct Energy Deposition (DED)	
Geometric complexity	●●●●●	-	●●●	-
Max. build size	●●●	500 x 280 x 320 mm	●●●●●	2,000 x 1,500 x 750 mm
Build-up on existing components	●●	-	●●●●●	-
Dimensional accuracy	●●●●	0.04-0.2 mm	●●	0.5-1.0 mm
Surface roughness Ra	●●●	7-20 µm	●●	4-40 µm
Post processing *(optionally)*	powder, support & substrate removal, *(stress relief, hot isostatic pressing, milling, polishing)*		powder removal, *(stress relief, milling, polishing)*	

Depending on application cases, products are required that are only partially suitable for AM due to their geometry or material properties. For example, the production of simple components, most of which could be designed as semi-finished products (e.g., rotor shaft element (2)). The hybridization of processes and components is a possible solution in order to be able to produce components optimally in terms of functionality, economy, and sustainability in accordance to the product's requirements. As described in Table 1, PBF (here: more specifically SLM) allows components to be realized with complex geometries and integrated functions (e.g., elements 5, 6 and optionally 7), such as pinned surface structures (as described in [10]) that are applied to connect FRP components in multi-material parts. With LBMD originating from the classification of direct energy deposition processes, for example, metallic components can be joined (elements 2-3, 3-5, 5-6), repaired (elements 3 and 7), or coated with additional material, e.g., against wear (elements 3 and 7). Limited to simple geometries, it also enables, for example, the generation of surface structures (elements 2 and 6) or entire turbine blades (elements 6 and 7).

3.3. The Post-Processing Stage

Advantages that lead to the decision for the use of ECM include particularly the machinability of difficult-to-machine metals and alloys; e.g., hardness is not a restricting factor. Since ECM is a contact-free process, there is no tool wear nor any mechanical or thermal influence on the work piece's surface layer. Additionally, the post-processing of comparatively complex geometries is feasible, also with small dimensions. Apart from that, the functionality of ECM is based on the phenomenon of electrochemical dissolution. The work piece represents the anode while the tool is made the cathode. Both are dipped in the electrolyte solution, an electrically conductive fluid in Fig. 3. The dissolution process occurs when an external current is present [30].

As already mentioned in section 2.2, ECM used as post-processing step for AM parts is particularly useful for functional surfaces. Such functional surfaces are exemplarily shown in Fig. 2 as green lines (elements 3-4 and 5-6). Especially friction surfaces, i.e. the contact surface between elements 3 and 4, require comparatively high quality. ECM is able to produce surfaces with a defined roughness [21], which also have the properties to withstand a steady friction use. Again, due to tight dimensional tolerances, the application example shows a huge demand for high-precision machining of element 5 and 6 to be able to fulfill a form fit between those elements.

3.4. The Non-Destructive Testing and Condition Monitoring Stage

Ensuring the quality of structural components is one major challenge, especially for safety critical applications. In general, this task needs to be achieved for the whole (multi-material) compound structure. Therefore, each component itself as well as the interfaces between adjoining parts need to withstand the local quasi-static and cyclic stresses caused by the operating loads. The focus in this stage lies on condition monitoring and reinforcement strategies for the interfaces, as those represent damage-critical areas in the given multi-material application example.

For the connection of FRP and metal (interface 1-2 and 6-7 in Fig. 2), hybrid joining strategies like bonding-bolting enable improved joint strength, fatigue life and energy absorption. However, the insertion of bolts or rivets through boreholes leads to reduced cross-section, damaged fibers, stress concentrations and mass increase. Fortunately, a novel hybrid joining scheme called hybrid bonding-pinning can overcome these issues and enables an outstanding joint performance [10]. The pins with a diameter of usually less than 1 mm are inserted into the dry or wet laminate prior to co-curing, using the matrix material as adhesive. AM is particularly suitable for the surface structuring of both, AM parts and pre-products. However, only little research has been done so far concerning the occurring damage mechanisms [31], especially with regard to lifetime prediction and management. Design and areal density of the pins determine the joint performance and affect the propagation of damage. Therefore, defects existing in the metal pins or the interface, respectively, are assumed to be particularly crucial for the overall joint performance. However, the effect of such defects is mostly unknown. For the characterization and damage monitoring of hybrid joints, thermography and ultrasonic guided SH-waves are convenient. The former has shown to be suitable for in-situ damage monitoring occurring at internal interfaces in FRP-metal hybrid structures (e.g., [32]) and the latter to evaluate the quality of bonding in metal-polymer interfaces (e.g., [33]).

4. Discussion and Outlook

Starting from a broad range of scientific approaches regarding individual considerations of designing, manufacturing and post-processing as well as quality inspection aspects within the innovative development of AM components, the presented contribution focuses an integrated framework for the AM product development of multi-material parts by meeting the contemporary aspects of efficiency, customization, and relocalization. Based on this, an appropriately initial analysis is highlighted on an integrated partly additive manufactured rotor propeller shaft.

Future work will have a look at many aspects. First, an advisory tool for the comparative (AM vs. conventional) selection of most sustainable manufacturing processes is emphasized, meeting product requirements and interacting within the process chain with design, post-processing, and non-destructive testing. Respectively, the post-processing stage will focus the use of ECM especially for SLM components, wherein future experiments should give a comparison in machinability, dissolution behavior, and reachable surface quality between conventional and AM parts. However, efforts regarding the characterization and damage monitoring of pinned hybrid joints (FRP-metal components fabricated by SLM or LBMD) using various NDT methods like thermography and ultrasound are additionally brought into focus in order to enable a description by means of probabilistic fracture mechanics.

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