Enabling Graduate Students to Design for Additive Manufacturing through Teaching and Experience Transfer

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ENABLING GRADUATE STUDENTS TO DESIGN FOR ADDITIVE MANUFACTURING THROUGH TEACHING AND EXPERIENCE TRANSFER

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ABSTRACT
The cyclic manufacturing processes of Additive Manufacturing (AM) create three-dimensional objects layer by layer, offer a large freedom in design, and suffer from very different restrictions compared to conventional manufacturing processes. Nowadays, AM is a mature manufacturing technology capable of being applied in industrial series production.
However, the AM technology enters the industrial series production only slowly. A main reason is the fact that engineers in industry have little to no experience in Design for Additive Manufacturing (DfAM) and an integrated experience transfer in engineering education is not yet widespread.
To implement the AM technology, a course for graduate students was developed and established, mainly in the master studies and in the field of mechanical engineering. The goal of the course is that the students gain experience in the possibilities and the restrictions of DfAM. The course is based on the Experience Transfer Model (ETM) and is divided in two parts, a lecture and a team project. In the lecture, the students gain explicit knowledge for DfAM. In the practical team project, the students develop and produce AM prototypes based on a variety of AM processes and gain implicit knowledge. The concept of the team project is based on Problem-Based Learning (PBL). The whole team project follows a product development process, including presentations of milestone. The physical outcomes showed that the students are able to design AM optimized parts without falling back into old design patterns. In a survey at the end of the lecture series, the students gave the authors feedback. The large majority of the feedback was positive.

Keywords: Design for Additive Manufacturing (DfAM), Engineering Education, Design Education Product Development, Experience Transfer Model (ETM), Problem-Based Learning (PBL),

1 INTRODUCTION

Additive manufacturing (AM) is the formal term for 3D printing and refers to a group of manufacturing processes which creates three-dimensional objects from the CAD model by adding material in a layer-by-layer process [1][2]. The first AM technologies were developed in the 1980s and were mostly used for rapid prototyping. The current application of the AM technology goes far beyond rapid prototyping [3]. AM now is mature for industrial production, and processes like Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) become feasible for a growing number of industrial end-user applications [4][5][6].

AM offers a large design freedom. Geometries can be produced which are unfeasible, or at least difficult, to produce by conventional manufacturing processes. However, there are limitations in the design such as orientation properties, poor surface roughness, especially on down side surfaces, and a need for post-processes like support removal and powder removal. [7]

A large number of design guidelines exist ([1], [7] [8] [9] [10]). However, these design guidelines are entering industrial practice slowly [11]. A main reason is their theoretical focus. To transfer the design guidelines to engineers, a lecture is recommended for students in engineering education [12]. Up to this course, an experience transfer for DfAM in engineering education exist very rarely. On the one hand, the earlier in a design career that design for AM is introduced the better. Otherwise, conceptualization and detailed design might be dominated by conventional manufacturing process limitations, which hinders realizing the full potential of the design freedom of AM. On the other hand, based on their previous experiences, students with some fundamental knowledge in designing a product will better understand, the AM's design benefits [4]. The lecture addresses graduate students after the Bachelor degree, because these students have a basic knowledge about design to understand the advantages of AM, but their mindset is not yet dominated too strongly by the design for conventional manufacturing process limitations. So this is the right time for engineering education to transfer knowledge for DfAM.

Some lectures for DfAM have already been launched, applying only the method of Problem-Based Learning (PBL) [13][14]. In contrast to the already existing lecture concepts, the lecture, developed and descriped here is based on the ETM, and the students produce a powder-bed-based prototype, using AM and receive frequent feedbacks from the lecturer.

The paper proceeds as follows: First the theory and the concept of the Experience Transfer Model (ETM) and PBL are introduced for the lecture Design for Additive Manufacturing (DfAM). Subsequently, the results of the lecture are presented, whereby one sample product is described in detail, while the other products are presented briefly. Finally, this paper presents the learnings of the students during the course.

2 THEORY AND CONCEPT

The course contains two parts. Within the lectures the explicit knowledge of DfAM and product development is transferred. The lecture is less held as a speech than it is a discussion between the experts and the students. In parallel to the lectures a team project is selected, in which the students gain implicit knowledge for DfAM in the field of product development.

Within the scope of the course, two theories are applied. First, the framework of this course is based on the ETM. In the ETM the knowledge for DfAM is transferred. Second, based on PBL, the students generate integrated skills in the team project. The skills from the project are especially important in the interdisciplinary field of product development. PBL is applied to systematize the course in order to confront students with problems from industry to trigger their learning process.

The ETM was originally developed to transfer experience knowledge for DfAM from experts to workshop participants. Explicit knowledge describes a factual knowledge and is clearly teachable in a lecture [11]. Implicit knowledge can be acquired by gaining experience, but it is difficult to transfer this knowledge [15]. The ETM is especially important, because human education is based on experience [11][16]. Up to now, the ETM was successfully applied to transfer knowledge to participants who are design engineers with many years of practical industry experience. The ETM describes a systematical approach by three steps: Input of theory about AM, implementation of the AM knowledge, and reflection of the AM knowledge [11]. In this paper, the ETM is applied for graduated engineering students with at least a Bachelor in engineering, mostly with the focus on product development.

For engineering education in product development, explicit knowledge of DfAM is not sufficient. The students need to generate more skills. In PBL students use impulses of the problem case or scenario to define their own learning objectives [17]. In PBL the students develop learnings for capability rather than learning explicit knowledge [18]. Based on small groups, PBL is a strategy not only for teaching, but of a sustainable learning of the students, guided by an expert [19]. PBL uses appropriate problems to increase understanding. Group learning facilitates not only the acquisition of knowledge, but also several other desirable attributes, such as communication skills, teamwork, problem solving, sharing information, presentation skills, and respect for the views of the colleagues [17]. The overarching objective for the students of this course is to gain implicit knowledge of DfAM, particularly in the field of product development.

3 COURSE IMPLEMENTATION

The first course in DfAM was held weekly in the autumn semester 2017 and from now on it is an annually repeating course. The 20 students received 4 credits after successful participation. Figure 1 shows the schedule of the course. On the abscissa, the lecture topics are plotted, where mostly the explicit knowledge is transferred. On the ordinate, the project phases are plotted. Within the team project the implicit knowledge is transferred.

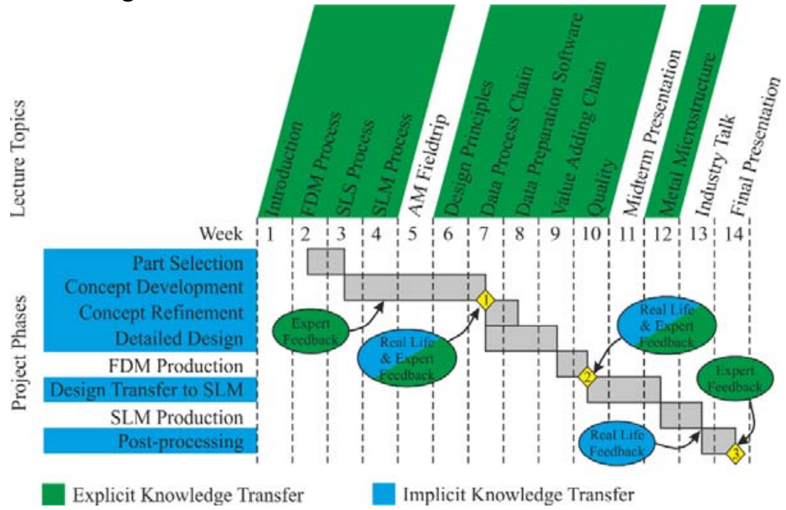

Figure 1. Gantt chart of the course, including the explicit and implicit knowledge

Within the lecture, the topic of the particular week and the status of the team project complement each other. After the introductory lecture, the students received input about the three most important processes in the field of AM. Within an AM exhibition, a variety of AM processes were demonstrated in the industrial practice. In the following lectures, the students continuously received input about the relevant topics of their current project status. The design principles were then introduced such that the students could apply them in the team project. The students also received input about other relevant fields of AM such as data process chain, data preparation software, value-added chain, quality and materials and microstructure of AM metal. At the end of each lecture, the students had gained new knowledge about the relevant capabilities and the limitations of DfAM.

The implementation period started in parallel to the input period. The teams brainstormed potential concepts for AM parts. The parts they identified or invented, such as the “Attachment of a GPS Transmitter for Elephants” (Figure 4.). The student teams developed an AM concept and a first design prototype for MS 1. For MS 2, the students prepared and presented a prototype made out of FDM. After MS 2 the students redesigned their FDM prototype to an SLM prototype made out of stainless steel. For one application, the final prototype was predestined for SLS because it had low load forces and strict weight requirements.

After each presentation, the students continuously reflected the parts, concepts, and prototypes in the form of a discussion, together with the lecturers, who are experts in AM, and the audience. Here, the students received both, feedback from the experts and real-live feedback from the prototype. After the fourth lecture, the students gave their first presentation and received an expert feedback about their ideas of potential AM parts. Accordingly, the students produced three prototypes, and out of every prototype, they received real life-feedback about the design, post-processing, and the function. In the 13th lecture, a speaker out of the AM industry explained his experience in the field of DfAM.

Within the team project, PBL is applied. In the team project, the students define their own teams with a maximum of five students. In the team, they identify their own parts and define their goals under the guidance of the experts. The goal of the students is to develop an AM prototype which fulfils the specific functions they defined. Within the project, the students are guided by AM experts. Every student has at least one part of a presentation for a few minutes. Every student presentation and discussion is recorded by a video camera to enable the students to reflect the performance from another perspective.

Figure 2 a) shows impressions from the lecture, including the student presentation, b) applying hands-on skills for prototyping, and c) manual machining of the final SLM parts.

The students specified themselves how the parts would be oriented and where the support structures would be attached. After Lecture 13, the students received their SLM and SLS parts, still connected to the base plate shown in Figure 3. The students had to remove the SLM parts from the base plate manually and to finish the surface on their own under the health and safety compliance rules for SLM parts. In the final presentation, for MS 3, the students presented their results in the form of a live demonstration and a video of their product.

a) b) c)

Figure 2. a) lecture and student presentations, b) creating design prototypes, c) Hands on for the SLM prototype

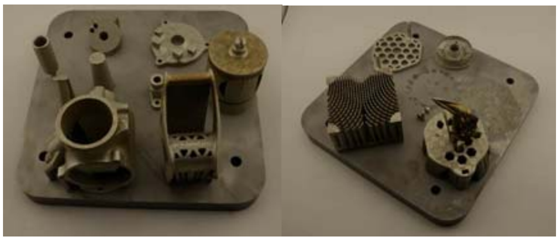

Figure 3. The base plate after the SLM process, before the students removed the parts and post-processed them

While the students applied their hands-on skills on the products in the form of prototyping and post-processing, they reflected their development work. For instance, they realized that support structures are hard to remove in locations that are difficult to reach. On the other hand, they identified the effects of thermal stresses. The students summarized and reflected their learnings in a report at the end of the student project. After the final presentation, the student teams reflected their team projects in a discussion with the lectures.

4 PHYSICAL OUTCOME AND FEEDBACK

During the course, each of the five teams developed three prototypes. The final AM prototype was validated in their corresponding system at the end of the course. One prototype is the so-called "Attachment of a GPS Transmitter for Elephants" (Figure 4). Its unique future is the rotating friction bearing, which the students designed directly into an FDM prototype, and an SLM prototype. The function of this part is to use a flying drone to attach a GPS transmitter in the ear of an elephant. In Figure 4 a), the working principle of the attachment is briefly plotted. In the first step, the arrow pierces the ear of the elephant. In the second step, a spring mechanism rotates the top of the arrow. In the third step, the attachment of the GPS transmitter is fixed by the folded arrow. In Figure 4 b), the three stages of the prototypes are shown. By using the design prototype, the students showed their concept. In the FDM prototype they showed the function of the prototype, including a translating and a rotating movement.

At the beginning of the first prototype stage, the part design looked conventional. But the development of the prototypes showed that the students continuously improved their parts and their knowledge of DfAM (Figure 4).

The final AM parts were presented and validated by the students in the form of real-life tests, by interacting within the overall system (Figure 5). A light-weight slack-line weblock was validated by introducing a load of a slack-line in the form of a live performance. A throttle body of a race motor cycle was assembled in the engine and the rotation tested. The rotation of a camera gimbal was validated on a quadrocopter. Finally, a thermal cycler was tested by analyzing the volume flow of fans through the SLM parts.

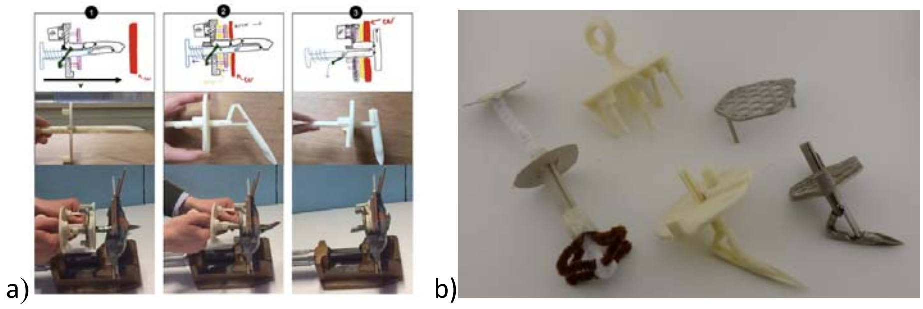

Figure 4. Attachment of a GPS Transmitter for Elephants; a) Top, scratch of the function process; middle, testing of the FDM prototype; Bottom, manual validation of the SLM prototype. b) Design prototype, FDM prototype and SLM prototype

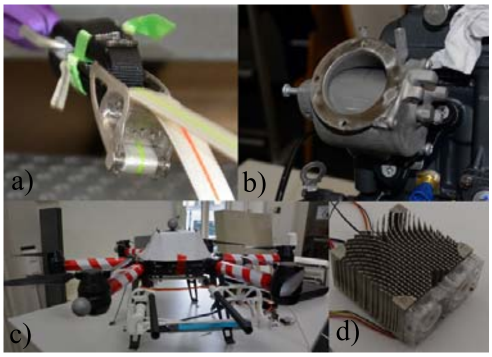

Figure 5. Physical outcomes: a) slack-line weblock; b) throttle body for a race motor cycle; c), camera gimbal on a quadrocopter; d) thermal cycler

In the final lecture, 18 of the 20 students in the course took part in an evaluation survey. The questions were to be answered by yes, no, or perhaps. The students were asked the following questions (Table 1):

Table 1. Survey of the lecture

Question	Yes	No	Perhaps
Was the team project important for me, to understand the content of the lecture?	16 (88.9%)	0	2 (11.1%)
Were the AM field trip and the industry talk important for me to understand the practical applications of AM?	13 (72.2%),	3 (16.7%)	2 (11.1%)
Will I recommend the course to my fellow students?	17 (94.4%),	1 (5.6%)	0

In the feedback questionnaire, the students had the chance to add comments. The large majority of the feedback was positive.

5 CONCLUSION AND OUTLOOK

Design guidelines for DfAM enter the practice slowly. To accelerate the transfer of the guide-lines, a course for engineers was developed. The objective for the students of this course was to gain explicit knowledge from AM experts and generate implicit knowledge of DfAM, through the application in product development.

During the course, the students received insights in the following topics: From the concept, design, data preparation, and post-processing, the students experienced the whole AM process chain. The systematical approach of the course led the students through the team project where they received expert feedback and real-life experiences from various prototypes.

The physical outcome showed that the application of the ETM lead to a successful experience transfer of explicit and implicit knowledge of DfAM to graduate students. Based on the basic pre-design knowledge of the students, the students added specific implicit knowledge of DfAM without falling back into old design patterns of conventional manufacturing processes, which is proven by the physical outcome where the students generated an AM-optimized design. By applying PBL, students successfully developed skills which are important for engineers, especially in the field of product

development. The final AM parts showed that all teams were able to successfully design and manufacture AM parts. The authors received a significant positive feedback from the students in a survey at the end of the lecture series, which highlighted the success of the course.
Based on the experiences out of the course, the students now are capable of implementing and fostering the AM technology in industry to generate added value for companies. In addition, the students are able to apply their skills to solve problems in a team, which nowadays, in the highly technologized world, is important for engineers.
For the next semester, the students should apply for the course by submitting their own idea of an AM part before the course starts in order to further increase the intrinsic motivation of the teams.

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