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Design for Additive Manufacturing Education of Process Engineering Students on an Industrial Challenge

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Abstract

As the use of additive manufacturing (AM) is increasing in many sectors, the need of design education for AM has gained importance. Solving the challenges of an application with the advantages of AM requires competencies in selecting a suitable AM process, identifying design opportunities and designing for AM based on an extensive knowledge in the application domain. Hence, it is necessary for all branches engineering to develop AM skills and competencies. This paper describes a lecture and practical to develop AM design competencies in chemical process engineering master students. The course teaches designing complex AM parts based on the need of an application by combining the opportunistic and restrictive aspects AM design with the domain-specific functional requirements. The design education benefits from AM's advantages in rapid prototyping to provide feedback within the time frame of a course. In order to fulfill the above requirements, an application-oriented design course from requirements to testing, involving a simplified real industrial design problem, has been prepared. Students obtain design requirements at the beginning of the practical and have to develop a device using the advantages of AM. After completing CAD design, the designs of the students are produced with the laser based powder-bed fusion of metal (PBF-LB/M) and bath-based photopolymerisation of polymers, curing using ultraviolet light (VPP-UVL/P) methods. The manufactured designs are tested on the test bench provided by the institute. A case study of a hybrid manufactured reactor with internal condensation supports the conclusion of this paper.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Additive manufacturing offers a high degree of design freedom, allowing for the production of complex components with enhanced performance. Additionally, AM allows for the design of product assemblies with fewer components, capitalizing on the functional integration advantages it provides. As highlighted by Gibson [1], AM changes the way to design products, because it accelerates not only the manufacturing processes, but also the product development. Owing to rapid manufacturing, CAD designs can be realized within a matter of days, without the delays associated with traditional supply processes. However, this convenience also introduces new challenges.

One of the main challenges is that the potential of all the advantages of AM is not fully utilized in industrial applications, mainly due to the lack of product design experts familiar with this technology [2, 3, 4]. To address this shortage and train more AM experts, knowledge transfer is essential, especially in two important areas: Design for additive manufacturing (DfAM) and rapid prototyping (RP).

In recent years, several studies have been published on how to support product designers with both restrictive and opportunistic approaches to DfAM. Despite the considerable design freedom AM offers, each AM method comes with its own set of manufacturing constraints [5]. Restrictive methods guide product designers in creating manufacturable designs, whereas opportunistic methods stimulate creativity during the

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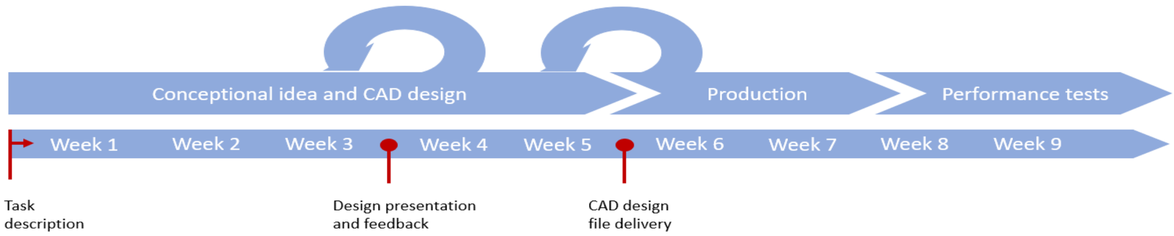

Fig. 1. Overview of lecture schedule from task description to performance tests

conceptual design phase of product development [6]. To design a successful product for AM, it is imperative to embrace both of these methods over the whole product development process. However, due to a lack of experience in using these approaches and their real-life applications, knowledge of DfAM should be transferred to product designers through AM workshops or graduate-level courses [2, 3].

RP facilitates the direct creation of 3D products from computer-aided design systems, significantly improving prototyping practices in the industry [7]. This approach enables verification of conceptual design performance at an early stage of product development, minimizing the risk of design failure due to a mismatch in customer requirements, technical design or manufacturing and maintenance issues [8]. Awareness of rapid prototyping is crucial for engineers to design successful products and should be incorporated into their engineering education. Mature AM processes enable a fluent transition from rapid prototyping to on-demand production and incremental product launches in a growing number of applications [9].

According to Rafi et. al, effectively integrating AM into industrial practices demands combining knowledge from various disciplines, practical experience dealing with real-world challenges, and customized training programs tailored to specific industry requirements [10]. With the realization that AM technology can make a difference in fields other than mechanical engineering, the learning of DfAM and RP is becoming increasingly important in other fields as well. However, new challenges arise in the education of engineering students, such as process engineering, where the traditional focus may not adequately address the nuances of AM. To fill this gap, we developed an engaging, effective lectures and practical to develop skills and competencies of process engineering students in DfAM and RP (see Figure 1). It is also imperative to create measurable performance tasks that will enable students to concretely demonstrate the impact of their studies and promote a better understanding of the potential in the context of their field. Moreover, the performance task should be linked a real industrial application to avoid misalignment between the requirements of the chemical process industry and the available educational and training programs [10].

2. Design challenge

This paper highlights the critical importance of AM and the need for a transformative approach to design education for process engineers and its integration into industry. In order to train new experts in the field of AM, the authors underline the following aspects:

- Motivating students by showing the effects of their design decisions
- Expanding students' horizons and introducing them to new designs and production technologies with AM
- Provide knowledge transfer in the fields of DfAM and RP

To address these considerations effectively, a course for master students in process engineering was developed. The course consists of a lecture and a practical. The lecture provides a basic understanding of various AM processes, design guidelines, economics and quality. This theoretical input is complemented and expanded by a practical where the students apply their knowledge on a design task. The task for the practical design education was thoughtfully crafted to involve a certain level of process complexity, underscoring the significance of RP as an alternative to protracted optimization cycles conducted through simulations. However, this task also facilitates a straightforward evaluation and measurement of the design quality by a simplified test of the parts' performance through quantitative data, as recommended by Hofmann et. al [4].

In addition to process complexity, the task should present a broad solution space to encourage students' creativity without constraining their options. This freedom enables them to employ opportunistic DfAM methods, capitalizing on the inherent design flexibility of AM. It is important to note that students' creativity is closely tied to their knowledge of AM. To foster a deeper appreciation of AM's capabilities in design and manufacturing, this awareness should be imparted through theoretical lectures and, occasionally, hands-on experience. For this reason, new technologies can be introduced to students through pre-designed base patterns incorporated into the assigned task. This approach allows students to gain practical exposure to the potential of AM.

In the existing literature, there are a limited number of design challenges that address the critical aspects mentioned earlier. Hofmann et. al, for instance, introduced a challenge tasking students with designing a manometer, thereby offering a significant solution space in a real-life application [4]. Prabhu et. al also contributed by presenting a series of design challenges related to wind turbine blades, aimed at optimizing their performance [11]. Despite the valuable emphasis on the significance of DfAM and hands-on experience provided by these papers, there appears to be a gap in the literature concerning the direct connection between engineering students and ongoing real industrial problems. Furthermore, most of the existing papers predominantly focus on educational structures tailored for mechanical engineering. We identified a noticeable absence of design challenges for AM catering to education in other engineering disciplines. This paper strives to bridge this gap by introducing a novel, performance-based design challenge, specifically tailored to facilitate the effective transfer of AM knowledge to process engineering master students.

Process engineering education is primarily concerned with the design, operation, and control of devices responsible for the transformation of materials through chemical, physical, and biological processes [12]. Given the paramount importance of physical phenomena like heat and mass transfer, temperature and pressure management in apparatus design, AM holds significant potential to enhance the efficiency of these devices. To foster greater recognition of AM in the field of process engineering, the "Additive Manufacturing for Process Engineering" course has been offered at the Karlsruhe Institute of Technology (KIT) since 2020. This course comprises both theoretical and practical parts. Notably, the practical part is crafted to encourage students to create their own devices aimed at addressing simplified industrial problems and subsequently testing these devices in real-world applications.

In the initial two years of the course, students were tasked with a heat exchanger design challenge as part of the practical part [13]. This task lead the students to primarily work on the conceptual calculations associated with heat exchangers, while neglecting the crucial lessons related to DfAM and RP. Hence, the need arose for a fresh design challenge that could redirect the students' focus away from the conceptual calculations, which they had already encountered in various other courses, towards the essential concepts of DfAM and RP.

2.1. Motivating students by showing the importance of their designs

Creating a constructivist-learning environment is a powerful way to boost students' motivation, especially when they are tasked with tackling complex and challenging problems in the real world [14]. To foster such an environment for process engineering students, it is crucial to formulate a design challenge that captivates their interest by presenting a representative challenge from their engineering domain. This challenge should incorporate fresh ideas from emerging technologies and industry-relevant applications.

In the realm of process engineering, one research area involves leveraging the functional integration benefits of AM.

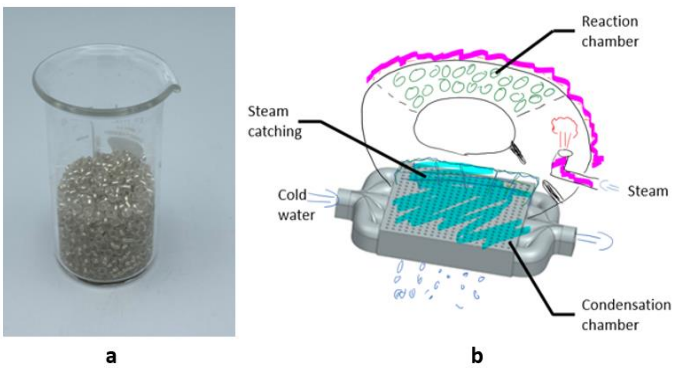

Fig. 2. Input for the design challenge of the practical part: a) Surrogate catalyst for the design challenge, b) Simple hand sketch to introduction of the design challenge

This area holds significant importance for both industrial applications and research facilities. Notably, at KIT and in collaboration with industrial partners, a reactor for methanol synthesis with internal condensation has been under development as part of BMWK 3D-Process project, supported by the federal ministry of energy and economy. This particular application involves two central process-engineering devices, namely a reactor and a condenser. By condensing the products it is possible to shift the concentrations away from the equilibrium and thus to increase the efficiency of the reactor. AM allows to combine both functions into an integrated device. Beyond its real-world relevance and popularity within the realm of process engineering, this design challenge offers students a unique opportunity to unleash their creativity in an industrial context. However, it is important to note that this task can be quite complex, involving intricate conceptual calculations and designs. To make it more accessible to students, we aim to streamline the design challenge and reduce its inherent complexity. Moreover, methanol synthesis, the chemical reaction at the core of this challenge, raises safety concerns due to the presence of toxic or flammable gases, elevated temperature and pressure. Consequently, for the safety of the students and the simplicity of the problem, the chemical reaction and the synthesis gases (e.g., carbon dioxide and hydrogen) utilized in the actual process are intentionally excluded from the problem definition. Nonetheless, even in this simplified problem scenario, it is impossible to ignore the significant influence of catalysts on essential factors like pressure drop and heat transfer. To mirror the real-world problem's complexities and make the challenge more realistic, small spheres, as displayed in Figure 2-a, are used as surrogates for real catalysts. This substitution allows students to grapple with the crucial interactions and considerations in designing process-engineering devices, without the added complexity of the chemical reaction itself. The concept of an integrated reactor and condenser was explained with the simple sketch depicted in Figure 2-b. This crude depiction was chosen to avoid favoring a particular solution concept.

2.2. Expanding horizon of the students introducing new design and manufacturing technologies with AM

Motivating students with a real-world challenge can significantly boost their creativity by bringing forth diverse ideas and different ways of thinking. However, students' creativity is closely linked to their level of knowledge. At times, it is essential to provide students with guidance on new technologies. Nevertheless, it is equally important to offer them a broad range of solutions to avoid stifling their creative thinking.

To achieve this goal, students are provided with a foundational design that allows them to explore the manufacturing potential of permeable structures using the PBF-LB/M method, relying solely on specific process parameters (see Figure 3). Permeable structures have become a prominent focus in AM research because of its wide range of potential applications in process engineering. Recent research indicates

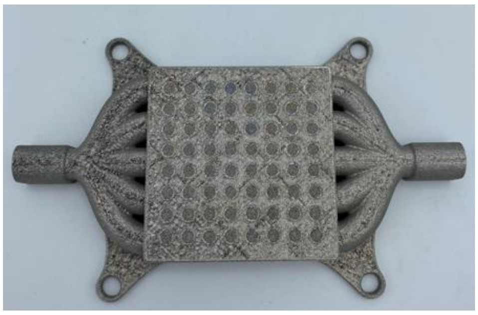

Fig. 3. Base design given to students with permeable structure

that the PBF-LB/M method can be effectively utilized to construct permeable structures in both production and other directions [15]. These structures, characterized by their high surface-to-volume ratio, hold significant potential in applications where efficient heat transfer is crucial. This highlights the capabilities of AM within the realm of process engineering. Nonetheless, introducing the concept of permeable structures to students is essential because this technology is relatively new and has only seen limited practical applications, making it a somewhat unfamiliar subject. In the context of the application the base contains a cooling system and channels with permeable material to extract liquid from the device.

2.3. Provide knowledge transfer in the fields of DfAM and RP

To enhance the learning experience and shift the focus toward DfAM and RP, the course incorporates both opportunistic and restrictive DfAM methods in the theoretical section based on Klahn and Leutenecker-Twelsie [16] before diving into the practical aspects of the course. At the outset of the practical part of the course, the design challenge is introduced through a simple hand sketch (see Figure 2-b). Subsequently, students are encouraged to apply DfAM methods to generate their design ideas. It is imperative at this stage to elucidate the critical functions of the desired design and present challenges to the students. In Figure 2-b, the design task specifies the requirement for a circular flow and students are asked to conceptualize this flow in their design. Moreover, the challenge of effectively filling and emptying the catalyst particles in the integrated reactor is emphasized in the task definition. The need to facilitate the introducing and changing the catalyst in the integrated reactor is a crucial consideration for the long-term availability of the reactor. The monolithic construction of the reactor adds complexity to achieving this functionality, making it an excellent opportunity for students to showcase their creativity.

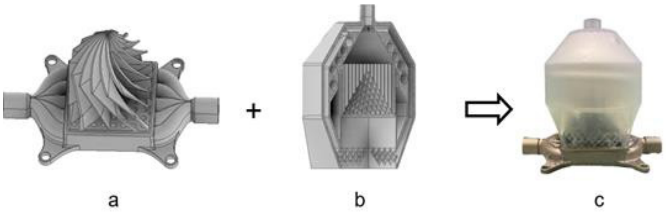

Fig.4. An example student design for the internal condensation reactor: a) Steam capture design, b) Circular flow reactor design, c) End internal condensation reactor before performance tests

Furthermore, to broaden students' awareness of various AM methods and their corresponding DfAM rules, two distinct manufacturing methods are applied to this design challenge. The challenge is divided into two parts:

1. **Part One: Steam Capture Design**

- Made from stainless steel 316L for an efficient heat transfer from the condenser surface to the cooling channels.
- Students are tasked with creating a steam capture design (see Figure 4-a) on a provided base design (see Figure 3) using PBF-LB/M method.

2. **Part Two: Circular Flow Reactor Design**

- Made from polymer for easy manufacturing and reduced heat loss to the environment.
- Design should respect PBF-LB/M design guidelines to allow a later change in material for methanol synthesis.
- Emphasizing the circular flow function, students are prompted to design a surrogate reactor capable of facilitating circular flow and holding a surrogate catalyst. This part encourages students to explore alternative AM methods using VPP-UVL/P method (see Figure 4-b).

The students have been provided with specific boundary conditions for their design challenge. These include water steam at atmospheric pressure, a temperature range of 110-120°C, and a volumetric flow rate of 2L/h at the inlet of their design. Additionally, they are informed that the maximum allowable size for both VPP-UVL/P and PBF-LB/M parts is 90x90x100 mm. An essential aspect of the challenge is the consideration of connections. Since the automatic thread definition with "Hole" function in CAD software can not be realized for additive manufactured threads, the threads are designed by the tutors. To ensure the evaluability of the designs, the students are informed that their creations will be compared based on the amount of collected water at the end of the performance test. Furthermore, bonus points will be awarded for designs that use less manufacturing material and incorporate DfAM methods. To provide additional motivation, the winning design will be manufactured in a three-quarter model using only the PBF-LB/M machine.

3. Practical

In the initial week, students were encouraged to form groups, resulting in five groups, each consisting of two members, except for group 5, which had one member. Once the design challenge was assigned, the students had a three-week period to develop a concept and design using a CAD software of their choice. The students presented their designs to their colleges and tutors. Each team had a 15-minute slot for their presentation, followed by long discussions on the design concepts and manufacturing constraints. After this first feedback loop, the students had two weeks to refine and enhance their designs.

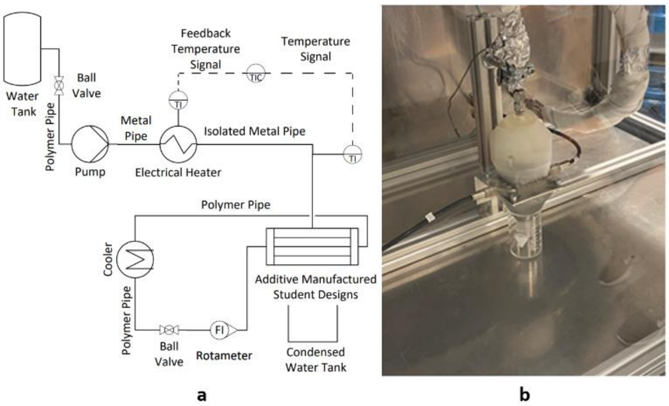

Fig. 5. P\&ID diagram of the test setup (a) and its operation (b)

By the end of the fifth week, the students submitted their refined designs to the tutors, marking the beginning of the second feedback loop. In this loop, feedback was provided to the students through bilateral meetings, focusing specifically on the manufacturability of their designs. Subsequently, the institute's VPP-UVL/P and PBF-LB/M machines were utilized to manufacture the steam capturing and reactor parts (see Figure 4). These parts were then assembled by gluing to create closed structures for the upcoming test. While multiple feedback loops are in place, it is possible that certain designs may be impractical for manufacturing using PBF-LB/M or VPP-UVL/P methods due to a lack of suitable design. Nevertheless, these designs are also deliberately produced to increase the learning curve from real-world feedback.

The performance tests are carried out after manufacturing of the designs. Students are briefed on the manufacturing process with the focus on powder and support removal before their designs undergo testing on a dedicated test bench (see Figure 5). The test bench realizes the condensation process using distilled water. The sequence involves pumping distilled water into the system, where a pump maintains a precise volumetric flow rate. The water is then evaporated in a heater with five heat cartridges. A controller and two thermocouples regulate the heater's temperature: one before the student designs to control the inlet temperature and another in the heater for safety. The steam is directed to the student designs through carefully insulated metal pipes to prevent heat loss and condensation before reaching the designs. In a second water circuit, a thermostat cools down water to facilitate steam condensation in the given base design in Figure 3. To maintain a constant volumetric flow rate in the cooling water at 2 L/h, a flowmeter is integrated into the system. This comprehensive setup ensures a thorough evaluation of the student designs, covering various aspects from water pumping and boiling to steam flow and condensation, all meticulously controlled and monitored throughout the testing process.

During the tests, it became apparent that the student designs were excessively intricate, making the removal of the carrier catalyst challenging. Therefore, this specific aspect was overlooked in the testing process, which focused solely on examining condensation within the designs and the circulation flow. However, this experience served as a valuable lesson for the students, highlighting the significance of testing and prototyping early in the product development process. It underscored that certain details may remain unseen until the designs are physically tested, as opposed to relying solely on the visualization within CAD software. Following the student design tests on the dedicated test bench, the condensed water was collected for each student team (see Figure 6). The water collected from each team is measured and compared against results from other teams. Additionally, feedback regarding material usage and the application of DfAM methods is provided to the students. This evaluation process is conducted interactively, allowing students the opportunity to assess designs from other teams and make comparisons with their own designs.

4. Discussion

The student designs highlight the benefits of additive manufacturing and underscore the significance of manufacturability, DfAM and RP aspects. The designs of three teams successfully condensed water during the test. Among these teams, one encountered challenges related to the manufacturability of their component. The design of another team was successfully manufactured, but it was too large to fit onto the test bench.

This practical exercise revealed that students experience a substantial learning curve when engaged in experimental work, irrespective of the success of their designs. Following the practical component of the lecture, students were given the opportunity to share their experiences verbally during the last lecture. They presented their designs and shared insights gained from the practical phase. Additionally, they provided feedback on the practical part and offered suggestions for the next year of the lecture.

According to the students' feedback, the internal condensation reactor design challenge proved more engaging than a heat exchanger design task. Consequently, their recommendation was to persist with the condensation design challenge in future lectures. Drawing from both the students' feedback and the authors' experience in the practical part of the lecture, it is apparent that this design challenge serves as an effective tool to enhance the learning curve of a student group, especially those whose primary focus does not revolve around mechanical design in their studies.

The authors can affirm that the design challenge successfully addresses the three aspects outlined in Section 2. Despite omitting the catalyst filling part during the test stage, students became aware of the complexities associated with catalyst filling problems in a monolithic design. Moreover, the design challenge encourages students to contemplate real-world industry applications. This has the effect of preparing students for AM technology and creates new job opportunities in students' careers. It is also noteworthy that the authors were able to leverage this design challenge for the BMWK 3D-Process project. During the test stage, an observation was made that circular flow in such a device resulted in water accumulation just before the permeable structure in the designs. The insights gained from this practical experience proved valuable for the later stages of the BMWK 3D-Process project.

In conclusion, the course has demonstrated that students whose main focus is not mechanical design can solve a design

Fig. 6. Collected water for each student design after performance tests

problem linked to a specific field by applying the teachings of different disciplines such as materials science, manufacturing technologies and design. This shows the adaptability of the course in other engineering disciplines.

5. Conclusion

Creating a dedicated AM design challenge for process engineering students in engineering education, with a focus beyond engineering design, serves as a valuable strategy to enhance the learning curve. This specialized challenge aims to motivate students by introducing them to new technologies and enabling them to apply these technologies in their own designs. By providing an opportunity for hands-on experience and practical application of AM, students not only acquire technical skills but also deepen their understanding of integrating emerging technologies into their future engineering projects. In this way, the level of preparation for the modern engineering workforce in the industry can be increased from the education of the students.

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