EDUCATION OF ADDITIVE MANUFACTURING- AN ATTEMPT TO INSPIRE RESEARCH

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Abstract

Although additive manufacturing technologies have undergone significant development in recent years, significant challenges remain in the understanding of the physics of the processes as well as many other aspects. Therefore, in the education of the next generation AM workforce, beside the instruction of existing AM knowledge, it is also of critical importance that the state-of-the-art research subjects and concepts are made aware to the students. In various classroom and lab setups at University of Louisville, contemporary AM research subjects are introduced to students via various tools including self-guided literature review, mini-research projects and design competitions. Through literature review based studies the students not only become aware of various research subjects, but also have the opportunity to practice critical analysis skills with new AM knowledge. Through the mini-research and the design competition project-based learning processes, the students not only gain hands-on experiences with AM practice but also learn about the research methodologies employed with various AM research subjects.

Introduction

First introduced in late 1980s, the Additive Manufacturing (AM) technologies have evolved into a large group of manufacturing technologies that are radically changing the horizon of the manufacturing industries via transformative capabilities in accommodating high levels of design complexity, design customization and production flexibility [1]. Over the past decade, AM has grown by over 50 times in terms of market size, and has maintained a growth rate of over 18% in the past 4 years [2]. Meanwhile, the applications of AM have also significantly expanded from predominantly prototyping, tooling and fixtures to many other functional components in high value-added industries such as biomedicine, aerospace, automobile, electronics and energy [2]. In many of these functional applications, the most sought-after capabilities of AM is the enabling of Design for Functionality (DFF), which focuses on maximizing the functions and performance of the structures with minimum resource consumptions (e.g. materials, production time, defect rate, etc.). This in turn requires that the users of the AM technologies are fully informed of the design capabilities and constraints introduced by AM. However, it is also broadly perceived that such knowledge base is currently not well established [3, 4]. Currently the existing knowledge with AM is still heavily empirical, especially in the areas of process development, manufacturability and design optimization [5]. In many application areas, specific knowledge and expertise that are based on individual products or specific material and process combinations usually lacks generality. Although the research and development of AM have gradually shifted towards more systematic investigation of the process physics in recent years, a coherent theory structure for many AM technologies remain an open challenge. Furthermore, the rapid evolution of the AM technologies aggravate this issue by constantly pushing the boundaries of the existing knowledge. For example, the recent development of the printing technologies for the fiber-reinforced composite materials has significantly disrupted the traditional view that AM lacks capability with this type of materials

[6, 7]. Similarly, the observation that the inert gas flow is a dominant factor in the occurrence of the spatter phenomenon in laser based powder bed fusion processes, which contradicts with the traditional perception that this is driven mostly by the keyhole recoil pressure [8].

With these challenges, effective AM education and training using the traditional lecture based learning is difficult. On one hand, a considerable percentage of the knowledge space exists in the ever-evolving horizon, which necessitates the constant update of lecture contents and the presentation of the state-of-the-art research in related areas. On the other hand, many of the newly generated knowledge are presented in fragmented scientific publications, which lacks systematic structures or even consistency and require extensive literature research. Such obstacle can be overcome by multiple measures. For example, the lecturer can perform literature research periodically and keep the contents updated and structured, or that the lecturers can prompt the students to perform such literature research as part of the learning experiences. The use of literature review as a learning tool has been reported previously in AM education [9], and in the author's teaching practices similar approach has been taken for the introduction of AM concepts and state-of-the-art applications, which will be introduced in more detail in this chapter.

As AM is still under intense development, there still exist many open questions and challenges that likely call upon continuous investigations. For example, in the investigations about the AM process quality benchmarking, despite various proposals about the benchmark artifact designs, there is still a general lack of consensus with the intended purposes and the effectiveness of these designs [10, 11]. Consequently, when such knowledge aspects are covered in the education processes, it becomes necessary to present it as an open subject. This not only makes the students aware of these contemporary issues but also encourages them to consider the problems from different perspectives. The exposure to these subjects in turn ensures that the next-generation workforce for AM can continue to dedicate to these critical issues and eventually provide solutions to them. There exist various pedagogical methods that facilities the critical thinking and active learning of specific subjects, such as debate based learning [12], project-based learning [13], group discussion [14], and problem-based learning [15]. Among these methods, the project-based learning can be effectively utilized to also implement hands-on learning with AM processes, which is a critical part of the AM education since many of the required skills for AM professions are closely related to the manufacturing operations. The project-based learning is commonly employed in AM education in many educational institutes in order to implement hands-on exercises, however in most cases the learning objectives focus on the comprehension of the freeform fabrication design concept enabled by AM layer-wise processes. Further development of teaching strategies are needed to effectively combine the existing strategies with the unique challenges of the AM education. In this chapter, some attempts in utilizing the project-based learning for the introduction of open questions of AM technologies are described in an effort to inspire future works in developing AM teaching methodologies.

Literature review based learning

The literature review based learning was employed in an introductory AM course in the Department of Industrial Engineering at University of Louisville. The basic concept of this method was previously described in detail [9]. The course consists of three components: the lectures, the student presentation and a semester project paper. Literature review based learning was employed as a major tool for the self-guided learning of specific subjects related to the AM technologies and their applications. The two parts of the semester project are elaborated in more detail below:

1. *Presentation*: the students will give a 30-45min presentation about the selected subject of literature review. The format and style of the presentation are generally unrestricted. However, the students were required to prepare the presentation as a "lecture", which will be consequently considered as the materials for the test.
2. *Paper*: the students will submit the literature review papers towards the end of the semester (about week 11-12), which will be reviewed and commented. The reviewed papers will be returned to the students for revisions, which mimics the journal article review process. The final version of the paper will be submitted at the end of the semester (about week 15 or 16).

At the beginning of the semester, the students were provided with the detailed instructions of the literature review project in order to encourage early preparations. A sample list of subject was provided as reference, which is partially shown in Table 1. The subjects ranging from AM applications (e.g. AM applications in dentistry) to specific state-of-the-art AM technology development (e.g. 4D printing) and some contemporary issues related to AM (e.g. AM cybersecurity). The students were encouraged to combine their personal or other research interests with the literature review and choose their own subjects. On the other hand, the students were required to submit a preliminary outline for the literature review sub-topics within two weeks of their initial subject identification in order to receive feedbacks regarding the scope of the works. This is because that the scopes of some of the subjects (e.g. AM in aerospace applications) could potentially be too broad and must be refined to fit into the scope of semester projects. The students work in groups of 2-3 members and proceed with the finalized subject afterwards.

During the first half of the course, lectures were given for specific AM technologies following the ASTM F2792 standards, which include material extrusion, vat photopolymerization, powder bed fusion, material jetting, binder jetting, directed energy deposition, and sheet lamination [16]. In addition, direct write technologies were also introduced as a separate category in order to give the students some perspectives about the multi-disciplinary AM systems. These lectures were expected to provide the students with fundamental understanding of the AM technologies that would allow them to perform more informed literature review works. Various aspects about general AM technologies, such as process physics, material compatibilities, advantages and disadvantages in practice, and current application areas, are introduced in the lectures. The contents of these lectures must be reviewed and updated by the lecturer every time the course is offered in order to ensure most up-to-date information.

During the second half of the semester, each student group would give the lecture presentation about the subject they chose for literature review. Due to the setup of such assignment as a "lecture", the students must ensure that the technical details are presented in clear and coherent ways. In addition, the presenters would be asked to also emphasize on the interactions with the audiences as well as the Q&A sessions, which was found to often significantly improve the engagement levels of student audiences for better learning outcomes. The lecturer would use the matrix listed in Table 2 for the evaluation of the presentations and determine whether the presented themes and information would be adopted for test questions. It is important that the students are aware of such process so that they would dedicate more considerations about the communication aspects with their presentations. Furthermore, such peer learning approach aims to achieve multiple objectives beside the communication of specific knowledge, including collaborative work, critical enquiry, communication and articulation of knowledge, self-management and self-assessment, which are also critical skill for many contemporary engineering working environments [17].

Subjects about AM applications	AM in medical applications such as bone implants, surgical planning, dentistry, external prosthetics, and tissue engineering; AM in soft and hard tooling; AM in foundry applications; AM in aerospace applications; AM in energy applications; AM in architecture and construction; AM in food industries;
Subjects about new AM technologies	4D printing; Organ printing/bioprinting; Multi-material or functionally graded material printing; Finishing technologies for AM;
Subjects about contemporary AM issues	AM supply chain issues; AM cybersecurity;

Table 1 Sample subjects for AM literature review project

Organization and content (20%)	(Graded by individual)
• Individual presentation organization/flow (good intro, transition flow)	1 2 3 4 5
• Use of visual aids (demonstrations, graphics, etc.)	1 2 3 4 5
• Use of time (fit naturally within 14-16 min)	2 4 6 8 10
Presence (15%)	(Graded by individual)
• Physical appearance (Adequate for lecture)	1 2 3 4 5
• Posture, gesture, movement, eye contact	1 2 3 4 5
• Enthusiasm, enunciation, clarify (no monotone, not too quiet)	1 2 3 4 5
Delivery and grammar (25%)	(Graded by individual)
Knowledge of materials and terminology (evidence of depth of knowledge)	2 4 6 8 10
Overall effectiveness of delivery method (ability to connect with audience)	2 4 6 8 10
Freedom from distracting "Uh"s, etc. (no nervous words or motions)	1 2 3 4 5
Overall	(Graded by group)
• Clear thesis statement and purpose (what is the main point?)	1 2 3 4 5
• Adequate support of thesis (how did you back up the main point)	1 2 3 4 5
• Overall material flow and organization (easy to follow, logical, smooth transitions)	2 4 6 8 10
• Definite conclusions (summarize main points)	1 2 3 4 5
• Overall completeness of topic coverage (any gaps in coverage?)	2 4 6 8 10
• Q&A session-knowledge of topic	1 2 3 4 5

Table 2 Grading criteria for the literature review presentation

For the literature review paper, the students were required to follow the author's guidance of popular AM journals such as Progress in Additive Manufacturing (Springer International Publishing AG, ISSN 2363-9512), Rapid Prototyping Journal (Emerald Publishing Limited, ISSN 1355-2546), Additive Manufacturing (Elsevier, ISSN 2214-8604) and 3D Printing and Additive Manufacturing (Mary Ann Libert Inc, ISSN 2329-7662). Each group would be required to include at least 20 journal publications, 10 conference proceeding publications, and 5 industrial articles (e.g. trade articles, company press articles) as the citation for their papers. As it was recognized that many students might not have adequate background for literature search, a lecture session was dedicated to the introduction of scientific publication database searching. Various literature search tools including Google Scholar, ScienceDirect, conference proceeding archives and article references were introduced to the students. The students would also have the options of actually submitting their papers to the journals if the subjects are deemed appropriate. On the other hand, regardless of whether these papers are eventually submitted as real journal manuscripts, the students would have the opportunities to enhance not only the understanding of the specific subjects but also various other skills, including technical writing, structured thinking, engineering problem identification and critical thinking. A sample grading rubric is shown in Table 3, which aims to provide the students with some guidelines about the paper writing. In Table 3, the technical review contents only consists of 25% of the grades. This is because that many of the technical content issues would be addressed in the initial review feedback. For literature review, the organization of materials and the structure of the paper are also of critical importance, and therefore are also emphasized (15% grade).

The use of literature review based learning was welcomed by the students, and many reported that they not only gained in-depth understanding with the AM technologies but also became more proficient with technical writing. Due to the broad range of subject selection, the students could usually identify ones that are of most interest to them, and therefore exhibit high level of motivation and engagement throughout the project. Some of the frontier subjects such as 4D printing and organ printing are constantly of interests to many students, which would give not only the review group but also the entire class the opportunity of in-depth learning of the subjects.

• Draft/final paper completed and submitted on-time	15%
• Good abstract and keywords	5%
• Followed formatting rules/appearance	5%
• Appropriate use of references	5%
• Appropriate use of figures	5%
• Grammar and spelling	5%
• Effective use of case studies/examples	10%
• Effective thesis/support/conclusions	10%
• Flow of paper/organization	15%
• Completeness of content	25%

Table 3 Grading rubric for literature review

Mini-research projects

Various open questions in the AM research and development fields can be potentially developed into project based learning materials. In the development of these projects, additional factors that should also be considered include the hardware capability of the educational facility, scope of project and the estimated time consumption. For example, for subjects related to the metal powder bed fusion AM process principles, the lecturer must make decisions such as whether to set up hands-on experiments using the often expensive equipment or computationally costly finite element simulation based studies. In addition, many of these open research questions would likely require additional refinement by the lecturer so that a subset of the problems can be set up as student projects. For example, in the discussions of the standard benchmark designs of AM, it was suggested that the benchmark designs could serve as geometry benchmark, property benchmark and process development benchmark [11]. As the simultaneous design of multiple benchmark types has been proved challenging, when setting this up as a learning project, one of the benchmark types such as geometry benchmark could be set up as the objective.

In the Design for Additive Manufacturing (DFAM) course also at the Department of Industrial Engineering at University of Louisville, various hands-on lab projects were set up as listed in Table 4. These projects attempt to cover a range of DFAM subjects from process capability investigation and material process-property characterization to lightweight geometry designs. The projects were also designed in a sequence that would facilitate progressive learning about the integrated DFAM theory. In the first lab project, the students were asked to use AM to design and realize a relatively simple real-world product with certain geometrical and mechanical requirements. Using the desktop material extrusion processes which has lower process resolutions, the students were set up to perform an “impossible” task, which would demonstrate the limitations of the AM product realization and the need of DFAM concepts. The second lab project aimed to help the students to establish the process geometrical quality design concept for AM, and was combined with the open research subject of AM geometric benchmark design. The students were given a short lecture about the current state-of-the-art research with the geometry benchmark designs and their design strategies. The students were then presented with various objectives with the geometry benchmark designs such as the characterization method for Geometry Dimensioning and Tolerancing (GD&T) with AM parts, considerations of variability with AM processes, and easiness of metrology. The students worked in groups of 2-3 and propose benchmark designs to the classes in competition for the final selection. The selected design would then be fabricated using various AM technologies (e.g. powder bed fusion, vat photopolymerization, material extrusion, binder jetting) by individual groups and consequently used for metrology. Fig.1 shows some of the benchmark designs proposed by students in the previous semesters.

Lab sequence	Lab project theme	Description
1	Using AM for product realization	Students would realize a product design with geometrical accuracy/strength requirements, such as a medical syringe or phone microscope
2	AM Geometric benchmarking	A geometric benchmark part design designed by students would be fabricated using various AM processes. The geometrical characteristics of each processes would be evaluated and compared
3	FDM process-property evaluation	Students perform experimental designs for FDM system in order to evaluate the effect of process parameters (temperature, scan speed, part orientation, part size, etc.) on mechanical properties of the structures
4	Geometrical design evaluation for cellular structure	Cellular structures with various unit cell designs will be fabricated and tested in order to compare their properties
5	Design efficiency of lightweight structure	Comparing the topology optimization design and the unit cell design and evaluate their efficiency and manufacturability

Table 4 Hands-on project for project based learning

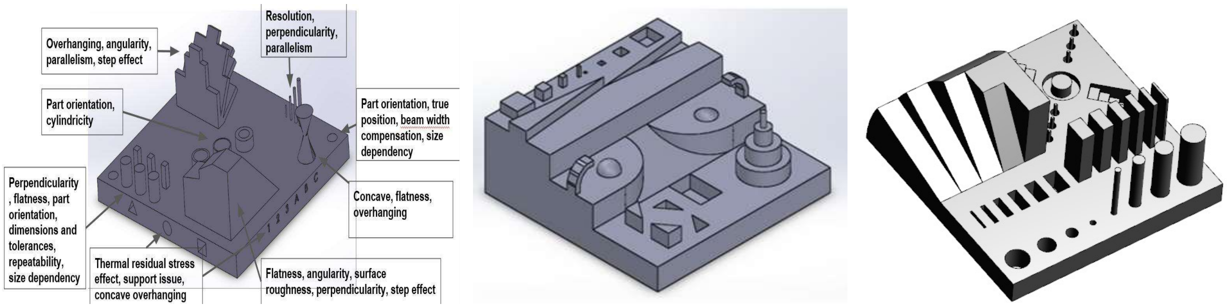


Fig. 1 Student designs for AM geometry benchmarking

Following the completion of the first two lab projects, the students would have opportunity to gain some additional in-depth understanding about the design for mechanical properties with the AM processes. This lab would focus on the introduction of the geometry-process-property design for the AM technologies, which is different from many traditional manufacturing processes that often allows for the separate design of geometries and material properties. This project was usually set up by using the material extrusion processes since the fabrication costs are relatively low. The design of material properties for the material extrusion structures include various aspects, such as the infill pattern, the number of skins/shells, the printing parameters (speed, temperature, bed preheating, etc.), the part orientation, the part dimensions, and the use of slicer software. In order to minimize the unnecessary implications induced by the software slicing algorithm, the project could be set up on a single printer. This also reduces printer-to-printer variability if such design factor is not intended to be investigated. Table 5 shows the experimental design table used for the investigation of mechanical properties of "standard" tensile coupons, while Fig.2 illustrates another project setup that focuses on the investigation of the effects of infill designs on the mechanical properties of the printed parts.

Printing temperature(°C)	205, 215, 225
Printing travel speed (mm/s)	100, 150
Angle of tilt (°)	0, 90
Coupon cross sectional size (mm)	3, 5, 7
Layer thickness (mm)	0.3
Number of shells	2
Infill density	20%
Raft	Yes

Table 5 Example experimental design for mechanical property evaluations of material extrusion AM

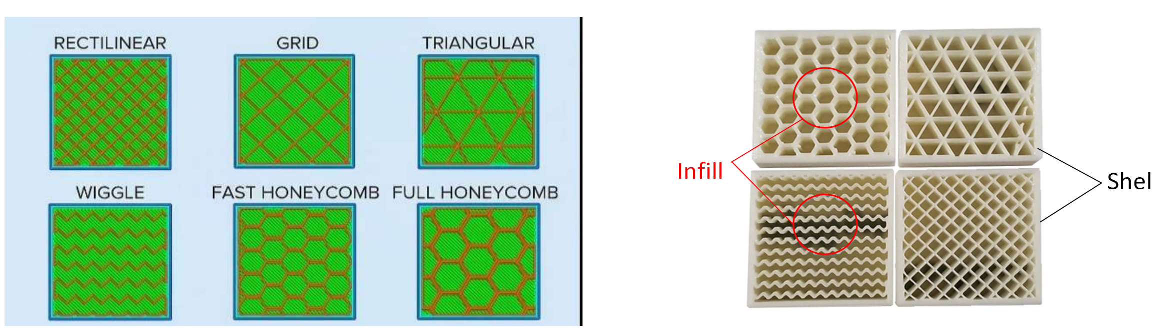
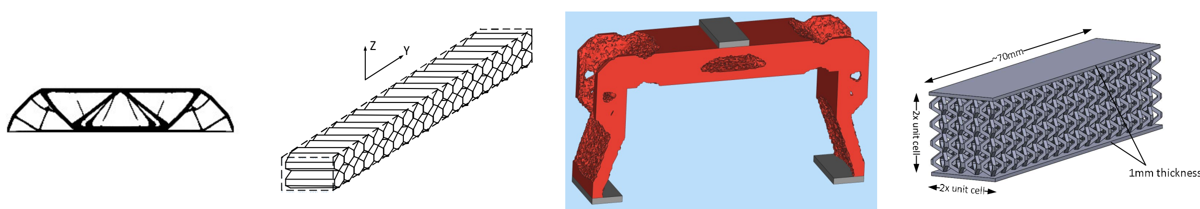


Fig. 2 Project example for infill pattern effect for material extrusion AM

The students would be normally given about 2-3 weeks to work on this project depending on the schedule and availability of the printers. Due to the large size of the experimental designs, the project was split into smaller experimental groups and assigned to each groups. Consequently, after collecting the testing results, the students would be asked to submit the data to the lecturer, who would compile the results and send them back to the class for the data analysis and final reporting.

In the last lab project, the students would focus on the design of AM lightweight structures. This subject has been of great interest for the AM research and development communities, therefore the focus of the project was to expose the students with different design methodology of AM lightweight structures, including the topology optimization and cellular designs. Depending on the AM platform intended to be used for the project, the level of complexity of the lightweight designs can be pre-defined to ensure manufacturability. For example, when material extrusion printers are used, the topology optimization designs could be restricted to 2D, and the cellular designs could be restricted to 2.5D extruded lattices such as honeycomb (Fig.3a). On the other hand, when laser sintering powder bed fusion processes are employed, the geometry design restrictions could be largely removed.



a. 2D designs (material extrusion) b. 3D designs (laser sintering powder bed fusion)

Fig. 3 AM lightweight design project examples

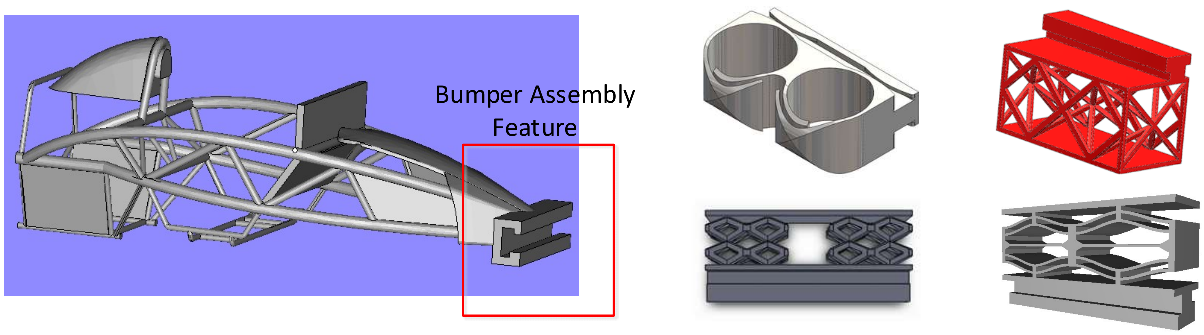
The students were asked to design for lightweight structures for static 3-point bending load for a bar structure using both topology optimization and cellular designs. For the topology optimization designs, commercial topology optimization software (e.g. solidThinking or Fusion 360) usually provide relatively straightforward topology optimization modules for single-loading cases and could be used by the students for the projects. For the cellular structure designs, the students were instructed to utilize unit cell based design methods, which could be realized via commercial CAD software. The lightweight designs could be evaluated potentially via finite element analysis (FEA), however the students were required to overcome potential practical issues such as file format compatibility issue and computational cost issues. The setup of this design project closely imitates the current engineering practice, which aims to not only facilitate the learning of the subjects but also give the students the crucial experiences for AM lightweight engineering designs.

Design competition

The semester project of this course was also setup specifically to stimulate knowledge synthesis and application. The project theme was set up as a lightweight component design for a "real" product, which required the students to combine the knowledge gained from the previous lab projects and to apply optimization synthesize with the knowledge in the design practices. One of such examples of project theme is the car bumper design. As shown in Fig.4a, the students were asked to design the car bumper that would be assembled to a standardized car body. The students were allowed to use any design methodology (empirical, theoretical, simulation) to achieve the design objectives below:

a. Maximum impact energy without damage on the car bumper;
b. Maximum impact energy without damage to the passenger.

Regular eggs were used as passengers to increase the level of challenges to the designs. As the design objectives are somewhat mutually exclusive and are difficult to achieve simultaneously, the students must utilize the knowledge learned from the course to devise optimized strategies. Such challenges are also currently encountered in the application of AM lightweight designs, which often result in different trade-off scenarios that are arbitrary and empirical. Such diversity in design preferences were also reflected in the course, which is illustrated in Fig.4b by the different designs used by the students.



a. Semester project design example b. Sample designs from students

Fig. 4 DFAM course semester design project

To increase the student engagement to the project, the final evaluation of the design was set up as a competition. As shown in Fig.5, the car-bumper assemblies were placed on a descending slope with egg passengers. The cars would slide down the slope and hit a relatively sharp object placed at the bottom of the slope in order to create the impact event. A short discussion session would be held after the competition to give the students additional opportunities to analyze the car bumper designs and summarize the learning outcomes. After the competition, the students would also be given additional time (1-2 days) to submit a final report with written analysis. By analyzing the final report and comparing it with the report of the first lab project, the learning outcomes of the DFAM theories could be quantified.

Fig. 5 Final evaluation competition of the semester project

Conclusive mark

There exist various challenges and risks in the integration of the state-of-the-art AM knowledge into the teaching practices. One obvious challenge is the relative lack of knowledge structure and sometimes even the validity of some of the conclusions. It becomes more difficult for the students to fully comprehend the problems when the overall understanding is still partial. Therefore, instead of teaching knowledge, a possibly more effective approach is to focus on the instruction of research landscape, which can be more difficult to evaluate outcomes for. In addition, it also results in additional pressures for the lecturers in the preparation. There is the risk of mis-instruction, which can result from the incorrect summarization of the literatures or the lack of clear conclusions. To avoid this, the lecturer must be keen to continuously follow the research and development trends in the AM fields.

Despite these challenges and risks, it is of crucial importance for the AM education to incorporate state-of-the-art research and development subjects. With the goal of educating the next-generation workforce in mind, it should be realized that unlike many other well-developed manufacturing engineering principles, AM will likely face rapid development for the coming decades, which makes it critical for the workforce to be aware of the dynamic landscape of the knowledge base and be more engaged in the continuous research and development efforts.

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