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Research on the Construction and Effect of a Full-Cycle Practical Teaching System Empowered by Additive Manufacturing Engineering for "Learning by Doing"

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Abstract: In the practical teaching of materials processing engineering, traditional teaching methods mostly stay at principle lecturing or repetitive experiments of single links, which easily lead to problems such as fragmented knowledge, superficial projects, non-traceable processes, and result-oriented evaluation. It is difficult to cultivate students' transferable engineering abilities. As one of the key technologies developed in the current industrial manufacturing industry, additive manufacturing (AM) engineering is characterized by strong coupling of design–process–manufacturing–testing–post-processing–verification–iteration, intensive process data, and prominent constraints on quality and standards. Through organic integration with teaching practice methods in the field of materials processing, it is expected to improve teaching effectiveness. This paper intends to construct a full-cycle practical teaching system of "additive manufacturing engineering empowering learning by doing". Driven by ability cultivation and supported by a project chain, students are trained through full-process participation in project implementation and data collection. Meanwhile, process quality is driven by review, and a closed loop is formed through multi-dimensional evaluation and continuous improvement mechanisms. Taking a typical engineering component project as an example, this paper discusses the teaching organization, data chain construction, and engineering delivery requirements of the training system, so as to form the effectiveness indicators for student training. This system helps to upgrade simple "hands-on practice" to an engineering training process that is "evidentiary, traceable, and reproducible", and promotes the cultivation of multi-level innovative and applied talents in the field of materials processing.

Keywords: Additive manufacturing; Full-cycle teaching practice; Project-based learning; Digitalization; Engineering delivery

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1. Introduction

In response to the urgent demand for applied and innovative talents in the field of materials processing engineering, the practical teaching methods in existing universities urgently need breakthroughs. Facing the complex and diverse knowledge system in the application field of this discipline, involving materials science, processing principles, process technology, material properties, mechanical manufacturing, etc., the traditional teaching practice system shows obvious deficiencies in the systematicness, integrity, and effectiveness of engineering practice [1]. Usually, it mainly relies on the characteristics of respective knowledge systems to carry out single-link and one-sided practical teaching, lacking the connection and integration between different practice systems, thus reducing the effectiveness of cultivating students' engineering application abilities [2].

Additive Manufacturing (AM) provides an innovative idea for the construction of a talent training system in the field of materials processing engineering. As one of the new intelligent manufacturing technologies focused on the development of the global industrial manufacturing field in recent years, AM technology is accelerating from "manufacturable" to "engineerable deliverable". AM technology integrates a variety of knowledge systems such as material design and preparation, liquid melting forming, 3D modeling, performance testing, simulation, mechanical system development, and digital integration. It is an advanced manufacturing technology involving a multi-disciplinary intersection [3]. In the industrial and scientific research sites of AM technology, whether a part is usable does not depend on "whether it can be printed", but on whether stable quality, traceable processes, and reproducible results can be achieved under clear demand boundaries, and engineering trade-offs can be completed under cost, cycle, safety, and standards. Additive manufacturing engineering covers the whole process of systematic procedures from surface material–structure design to process window convergence, process monitoring and defect control, testing and post-processing, quality system, and engineering delivery. It can be organically integrated with the theoretical teaching stages of different knowledge systems, which is conducive to improving students' knowledge understanding and practical abilities.

This paper proposes a full-cycle teaching system that deeply isomorphs the whole life cycle of additive manufacturing engineering with "learning by doing". The core goal is to carry out deliverable, traceable, evaluable, and iterative engineering practical training based on theoretical teaching. Supported by the project system, students are cultivated to form action, feedback, and reflection abilities in a real task situation [4]. Combining theoretical and practical teaching, a sound engineering application and innovative thinking are formed, answering key questions such as "why design like this, why select parameters like this, what is the defect evidence, whether the improvement is effective, and whether others can reproduce", so as to improve students' engineering application abilities and professional competence systematically.

2. Design idea of the practical teaching system "AM engineering empowers learning by doing"

Taking the whole life cycle of AM engineering as the main line, an innovative practical teaching system design idea of "system construction–teaching implementation–evidence collection–evaluation analysis–continuous improvement" is formed. In terms of system construction, based on industrial post capabilities and AM technology processes, a student training ability portrait is established and the practical teaching curriculum planning and project construction are reversely reconstructed[5]; in the teaching implementation part, supported by a multi-level project library, the learning process is organized into a series of milestone nodes, and a review mechanism is introduced to control process quality; evidence collection takes process data as the main line to run through scheme design, slicing and process parameters, equipment and process monitoring data, testing and performance data, and delivery reports or physical objects, forming an "evidence chain" of the whole life cycle of AM engineering; finally, in terms of evaluation analysis, an evaluation framework is constructed from the multi-dimensional perspectives of process, result, and ability[6], which can be used for both learning diagnosis and system iteration.

3. Construction of the full-cycle teaching system: From "activity-based practice" to "engineering isomorphic training"

The key to the full-cycle system is to establish a stable "traction–bearing–evidence–evaluation" mechanism, so that "learning by doing" has the rigid structure of engineering education. The engineering and evaluability of ability objectives are the key foundation for system construction. The ability training of AM engineering talents can be mainly summarized into four categories: material and structure design ability, process and manufacturing ability, quality and reliability ability, and engineering delivery and collaboration ability. The training system requires that each type of ability corresponds to a clear evidence carrier. Taking "material and structure design ability" as an example, its judgment method should not be simply limited to the ability to use software and equipment, but an evaluation system should be established in terms of "design version records, key decision descriptions, risk lists, and verification results". Similarly, "process and manufacturing ability" should be based on the basic ability training mode of equipment operation and parameter regulation [7], and further deepen the understanding and analysis ability of "parameter optimization scheme, process records, defect evidence, and window convergence logic". The cultivation of "quality and reliability ability" should focus on the formulation of testing criteria, the collection and analysis of testing data, and the process control of forming consistency judgment conclusions. At the same time, in terms of "engineering delivery and collaboration ability", a complete system of delivery integrity, data traceability, and result reproducibility is formed. Through this "ability–evidence" binding, the teaching goal is transformed from mastering complex knowledge points and simple skills to the organic integration of "guiding engineering practice based on theoretical knowledge reserve", promoting students' application-oriented engineering thinking construction, and laying a foundation for subsequent curriculum organization and evaluation closed loop.

In the process of system construction, the project chain is used as the carrier to carry out the whole life cycle of AM engineering practical teaching, avoiding single and fragmented repetitive experiments. The project library is organized hierarchically according to "basic training–comprehensive engineering–open innovation", which is accurately coupled with the training cycle of college students [8]. Basic training projects are mainly for the introductory stage, establishing standard awareness and process cognition in a short-cycle and high-feedback practical way; comprehensive engineering projects are for the professional advanced stage, taking typical engineering components as carriers, enabling students to correlate and understand the theoretical knowledge system with the whole chain of practical links such as actual engineering requirements, design, process, manufacturing, testing, post-processing, and verification; finally, in the implementation stage of open innovation projects, real enterprise needs or sub-tasks of scientific research projects are introduced, and team collaboration is the main development method to train uncertainty management and innovation verification abilities. The significance of project grading is that students at different levels can enter the "real but controllable" closed-loop engineering practice process [9], which not only ensures the bearing of safety and resources, but also ensures that learning is always in "constrained real application problems".

In the implementation process of the practical system, one of the key objectives is the construction of a database, and the practice process quality control is driven by review to cultivate students' project implementation and management abilities. Data management requires the formation of traceable evidence around the "technical data package", mainly including the collection, analysis, and induction of CAD/CAE and design documents, slicing files and structural parameters, process logs and batch information, process monitoring data (such as layer images/melt pool signals, etc.), post-processing records, characterization and performance testing, review and conclusion data. The review mechanism mainly includes demand review, scheme review, manufacturing review, delivery review, and other links. The project promotion process is based on the real engineering management and control mechanism [10], forcing students to think "why do this" at each key node, forming scientific engineering practice thinking, so as to upgrade hands-on practice to evidentiary demonstration and standardized expression.

4. Teaching implementation path: Curriculum organization, operation mechanism and typical project cases

At the implementation level of the "AM engineering empowering learning by doing" teaching system, emphasis is placed on the "modular support" and "multi-knowledge system series" of the curriculum group for project milestones, rather than the linear teaching of a single course. Curriculum content design relies on the early theoretical teaching knowledge system and is divided into modules by coupling the AM engineering process. In the safety and standard module, students are enabled to establish the relationship between curriculum theoretical teaching and the real manufacturing environment; in the design and simulation module, design scheme demonstration is carried out based on theoretical knowledge such as programming language, engineering drawing, and engineering mechanics, so that knowledge systems such as forming and stress control and support strategy directly serve the design review of typical structural parts of AM manufacturing [11]. In addition, in the process and manufacturing module, practical teaching is carried out around process window, scanning strategy, parameter optimization, and process anomaly identification, enabling students to use experimental design and data analysis to converge parameters instead of repeated empirical trial printing; in the characterization testing and post-processing module of typical components, practical ability training is carried out around professional theoretical teaching knowledge systems such as heat treatment, surface treatment, non-destructive testing, and structure-performance characterization. Finally, in the engineering delivery module, focusing on cost and working hours, quality system, traceable data, and project management, the learning results are closed in the form of engineering technology packages. In the training process of each module, it is not limited to the complete fit and coverage with the theoretical knowledge system, but focuses on curriculum work with the goal of "integrating theory with practice and cultivating the ability to solve engineering problems".

Taking "AM manufacturing of lightweight bracket components" as a project case, the whole process of its innovative practical training empowering "learning by doing" is described. The project starts at the demand review stage. The task statement clarifies the load and installation boundaries, size and weight constraints, material and process paths (such as laser powder bed fusion forming + heat treatment), testing requirements and acceptance criteria (key dimensional tolerances, internal defect thresholds, necessary mechanical performance indicators, etc.), and gives cost and cycle boundaries at the same time to ensure that students face real engineering constraints from the beginning [12]. Entering the scheme review stage, students take AM engineering technology as the main line to complete the structural design scheme, topology optimization or structural reconstruction, support strategy design, and submit key decision descriptions and risk lists (thin-walled areas, overhang areas, heat accumulation areas, potential deformation and support failure risks, etc.), focusing on evaluating whether the manufacturability demonstration is sufficient and whether the risks are controllable. After passing the scheme review and entering the manufacturing review stage, students need to form an executable process plan: slicing strategy, layer thickness and scanning strategy, preheating and shielding gas setting, forming and post-processing process, as well as parameter optimization scheme, and clarify the process record form and abnormal disposal rules. The manufacturing implementation stage requires students to operate in the way of "evidence printing", completely record equipment status, batch information and key parameters, and collect process monitoring data; if typical defects occur (such as lack of fusion, spheroidization, layer defects caused by abnormal spatter), a closed loop of "monitoring signal–defect verification–parameter/strategy adjustment–re-verification" must be formed. Entering the delivery review stage, students complete quality judgment based on testing data: dimensional measurement and geometric deviation, internal defects and pore characteristics, the impact of post-processing on structure and performance, trace back deviations and defects to design and process decisions, and give causal explanations and improvement suggestions. Finally, in the review stage, a review report is submitted in the structure of "problem–cause–countermeasure–verification–solidification", effective practices are precipitated into reusable assets (parameter packages, process cards, checklists or failure case entries, etc.), and the data package is filed into the project library, becoming a callable resource for the next round of teaching and research.

In terms of organization, the system usually adopts role-based collaboration to ensure process authenticity and responsibility implementation. Roles such as project manager, design director, process director, quality director, and data administrator are set in the team, requiring the person in charge to defend around the evidence chain at the review meeting [13]. Teachers, as "chief engineers/review experts", conduct inquiries, focusing on questioning boundary conditions, trade-off logic, and evidence adequacy. Role-based collaboration can significantly inhibit the phenomenon of "a few people complete, many people watch", so that each student must undertake visible responsibilities and deliver results on the engineering chain.

5. Popularization, constraints and countermeasures

The advantage of the full-cycle practical teaching system of "additive manufacturing engineering empowering learning by doing" is that it solidifies "learning by doing" into an operational engineering mechanism. Its popularization is mainly reflected in the following aspects. Driven by ability portraits, the project difficulty can be tailored according to the conditions of different schools and platforms while maintaining the ability structure; secondly, with standardized deliverables and data traceable main line as the core, even if the equipment and monitoring capabilities are limited, a basic evidence chain can be established through "process records + testing criteria + review solidification"; in addition, taking review as a process control means can improve practice efficiency and reduce invalid trial and error under limited resources. However, the implementation of the system also faces the following practical constraints [14], mainly in the comprehensive establishment of safety specifications such as powder management, laser safety, ventilation protection and access assessment, otherwise the full-cycle practice of AM engineering cannot be sustained; secondly, to ensure the reasonable allocation of equipment resources, it is necessary to balance through virtual-real combination, batch practice and centralized verification of key nodes; in addition, the workload of teachers' evaluation has increased significantly, but the solution is not to reduce standards, but to reduce the difficulty of later work through templating delivery packages, structured data packages and strengthening the process review system. More importantly, it is necessary to prevent the practical teaching system from degenerating into "formalized form filling" in operation, so review inquiries must be carried out around evidence to ensure that data and results truly serve engineering decision-making.

6. Conclusion and prospect

Aiming at the demand for applied and innovative talents training in the field of materials processing engineering, this paper proposes and discusses a full-cycle teaching practice system of "additive manufacturing engineering empowering learning by doing". The teaching practice system takes the whole life cycle of AM engineering as the framework, reconstructs courses and projects driven by ability portraits, carries real tasks supported by project chains, runs through evidence collection and result delivery with a data-traceable main line, drives process quality control with review, and realizes continuous improvement through multi-dimensional evaluation and case library solidification. The core contribution of this system is to upgrade the complex knowledge system and fragmented repeated experiments into an application-oriented training system closely linked with theory and practice, focusing on the "evidentiary, traceable and reproducible" engineering training process, enabling students to prove decisions, explain deviations and complete iterative optimization with data and criteria, so as to form transferable comprehensive abilities in materials and structure design, process optimization, defect analysis, quality control and engineering delivery in the field of materials processing engineering [15]. In terms of teaching system establishment, the future can further combine process monitoring data analysis and AI intelligent quality prediction, standard benchmarking and certification-oriented curriculum construction, and cross-school-enterprise collaborative project library co-construction to enhance the industry adaptability and scalability of the system, providing strong support for the cultivation of multi-level applied and innovative talents in the field of materials processing engineering.

Disclosure statement

The author declares no conflict of interest.

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