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Reform and Practice of Comprehensive Experimental Teaching in Material Forming and Control Engineering Based on the Cultivation of Innovation Practice Ability

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Abstract: The comprehensive experiments are a crucial component in cultivating the engineering practice skills and technological innovation capabilities of students, which play a significant role in training innovative application-oriented talents with the ability to solve complicated engineering problems. To address the current challenges encountered in the teaching of comprehensive experiments in the Materials Forming and Control Engineering major, Qilu University of Technology has systematically undertaken reforms and practices in the teaching system of these comprehensive experiments. This paper mainly introduces the teaching reforms in the comprehensive experiments of Materials Forming and Control Engineering from the perspectives of course design, teaching resources, teaching team development and evaluation systems. The results of the practical teaching demonstrate a substantial improvement in practical innovation abilities and scientific competitive awards of students.

1. Introduction

As a critical pillar of modern industry, the quality of talent cultivation in Materials Forming and Control Engineering directly influences the national industrial level and technological innovation capabilities. With the rapid advancement of technology and the advent of the Industry 4.0 era, the field of Materials Forming and Control Engineering faces unprecedented challenges and opportunities. Comprehensive experiments are an essential component in cultivating students' engineering abilities and enhancing their technological innovation capabilities, aiming to provide a thorough and integrated training of the theoretical knowledge and experimental skills they have acquired. However, traditional teaching of comprehensive experiments has often focused primarily on skill training and theoretical validation, lacking systematic cultivation of students' innovative thinking and comprehensive practical abilities. This teaching model often leaves students without sufficient creativity and problem-solving skills when confronted with complicated engineering problems, making it difficult to meet the modern industry's demand for high-quality innovative talents. To address this challenge, it is imperative to introduce a comprehensive experimental teaching model focusing on cultivation of practical innovation abilities within the education of Materials Forming and Control Engineering.

A variety of researches have been carried out on teaching reforms and practices relevant with the comprehensive experimental teaching model in the field of Mechanical Engineering. Zheng et al. [1] systematically introduced the reform measures for the comprehensive experimental system in the Materials Forming and Control Engineering major at Shandong University. They covered the aspects of teaching philosophy, teaching models, course framework, experimental content, teaching organization, teaching methods, experimental methods, assessment systems, and continuous quality improvement. Peng et al. [2] discussed the innovative teaching theories and reform practices in the comprehensive experimental course of Mechanical Engineering. They mainly focused on the design, openness, and comprehensiveness of the course through the development of experimental task books, organization of experimental processes, metallographic skills competitions, and comprehensive assessment of the experimental course. Li et al. [3] conducted a series of teaching reforms based on the current teaching status of comprehensive experimental courses in Mechanical Engineering, which addressed the experimental teaching system, teaching models, teaching methods, and assessment methods to stimulate students' interest in learning and innovative thinking. Liu et al. [4] redesigned the teaching process of industrial robot on-site programming experiments based on the BOPPPS teaching model and improved the grading method to ensure strict execution of each step. They found that, the new teaching model significantly improved students' initiative and enthusiasm in participating in experiments. Li et al. [5] reformed the comprehensive experimental teaching in Mechanical Engineering with the goal of cultivating students' practical and innovative abilities, and they constructed a project system, evaluation system, support system, and teaching model for comprehensive experiments. Wang et al. [6] took the design and measurement comprehensive experiment as an example, explored and practiced the restructured course system. They mainly focused on product solutions, developing experimental platforms and fostering industry-university-research collaboration.

The Materials Forming and Control Engineering Major of Qilu University of Technology is set up in the School of Mechanical Engineering, recognized as a top-tier program in Shandong Province. It aims to cultivate high-quality, application-oriented talents with a solid theoretical foundation in materials forming, advanced knowledge of control technology, and strong engineering practice and innovation capabilities. This major integrates multidisciplinary content, including materials science, mechanical engineering, and automation control. Students not only study the forming processes of materials such as metals, plastics, and ceramics, but also master related automation control technologies and modern manufacturing techniques. The present study uses the Materials Forming and Control Engineering major as a case study to analyze the challenges in the comprehensive experimental teaching process. It addresses these issues by building and implementing a comprehensive experimental teaching model oriented toward cultivating practical innovation abilities. The teaching process, teaching resources, faculty development, and evaluation systems of comprehensive experiments are discussed in details, in order to provide new methods and ideas for talent cultivation in the Materials Forming and Control Engineering major.

2. Current Status Analysis on Comprehensive Experimental Teaching

Comprehensive experiments are crucial courses designed to integrate students' acquired knowledge, aiming to develop their ability to solve complicated engineering problems. In universities like Tianjin University, Shandong University of Technology, and North China University of Water Resources and Electric Power, the curriculum for the Materials Forming and Control Engineering major includes a 2-4 week comprehensive experimental course. This course requires students to engage in various learning activities such as literature review, experimental design, implementation of experimental processes, and analysis of experimental results. These activities are intended to enhance students' engineering practice skills and technological innovation capabilities. However, despite these efforts, the current implementation of comprehensive experimental teaching in the Materials Forming and Control Engineering major still faces numerous challenges, which significantly affect the effectiveness of the experimental teaching.

2.1 Lack of literature review and experimental design processes

The traditional comprehensive experiment teaching often lacks a literature review phase, and students have insufficient understanding on the experimental background, cutting-edge technologies and existing research outcomes. This gap leaves students reliant on materials and guidance provided by instructors, with limited opportunities for independent thought and in-depth comprehension of the experimental issues. Furthermore, experimental design requires students to have a solid theoretical foundation, allowing them to apply theoretical knowledge flexibly to formulate a scientifically sound experimental plan based on the experiment's objectives. However, in most comprehensive experiments, the experimental plans are typically pre-designed by instructors, with students simply following predetermined steps directly into the experimental operation phase. This approach leads to a mechanical and monotonous process, where students lack an overall grasp of the experimental procedures, limiting their initiative and creativity during the experiments. Consequently, this deficiency hinders the development of their ability to solve real-world engineering problems.

2.2 Lack of ability in analyzing and summarizing experimental results

Unlike verification experiments, comprehensive experiments require theoretical analysis of the experimental results to draw valid conclusions. For example, in the metal fracture experiment, a verification experiment typically requires students to identify the fracture surface morphology corresponding to different fracture modes. In contrast, a comprehensive experiment demands that students analyze the failure modes of the material based on specific fracture morphologies. In traditional comprehensive experimental teaching, students often tend to simply repeat the experimental steps and record the data, without a deep understanding of the theoretical mechanisms behind the observed phenomena. In case of analyzing experimental results, they struggle to effectively integrate experimental data with theoretical knowledge. They are often unable to provide reasonable explanations or propose improvements when the results do not align with expectations. Additionally, students typically find it challenging to extract key conclusions from the experiments during the summarization phase, and fail to critically reflect on the shortcomings of the experimental process or offer suggestions for improvement. This deficiency in analytical and summarizing skills not only inhibit students' overall understanding and mastery of the experiment, but also obstructs the further development of their scientific thinking and problem-solving abilities in engineering contexts.

2.3 Limitations of experimental equipment and resources

Comprehensive experiments in the Materials Forming and Control Engineering major require advanced teaching equipment, such as X-ray diffractometers, non-destructive testing devices, shearing machines, hot rolling mills, heating furnaces, high-temperature resistance furnaces, benchtop grinders, metallographic microscopes, and analysis systems. However, in many universities, this type of equipment is either outdated or insufficient in quantity. As a result, students are often unable to fully engage with advanced materials forming processes and control technologies during their experiments. This limitation confines the experimental teaching content to basic operations, restricting hands-on capabilities of students and their understanding of modern engineering technologies. Furthermore, the scarcity of experimental resources leads to limited materials and simplified experimental conditions, which causes most comprehensive experiments to focus on traditional forming processes and basic experiments. Resource shortage hinders the exploration of new materials, new processes and modern manufacturing technologies. The narrow scope of experimental content limits the development of students' innovative thinking and fails to fully reflect the latest advancements and practical demands of the current industry.

2.4 Insufficient knowledge update and practical experience of teaching team

The Materials Forming and Control Engineering major encompasses multiple disciplines, including materials science, control engineering, and electronic information. However, many teaching members are deeply focused on their specific research areas and have relatively limited knowledge of other related disciplines. This specialization can restrict the diversity and comprehensiveness of experimental teaching. Additionally, some teaching members lack practical experience in engineering projects and are slow to update their knowledge and skills regarding new technologies and equipment. This gap hinders their ability to provide students with guidance that is closely aligned with real-world applications during comprehensive experiments and innovative practices. Moreover, the traditional experimental teaching model emphasizes theoretical instruction and basic experiments, with limited guidance on conducting innovative experiments. Teaching members often struggle to inspire students' innovative thinking and self-directed inquiry. This shortfall makes it difficult to engage students' enthusiasm and creativity through varied teaching methods, limiting the effectiveness of the experimental teaching process.

2.5 Monotonous assessment methods and insufficient effective feedback

The current assessment of comprehensive experiments primarily evaluates the correctness of experimental results and the formal standards of the experimental report. This approach overlooks formative assessments that consider innovative thinking, problem-solving abilities, teamwork, and other critical aspects demonstrated during the experiment. The assessment criteria are heavily focused on the end results, and students are often motivated to seek the right answer rather than engage in thoughtful exploration and innovation throughout the process. Consequently, students tend to follow predefined experimental steps and show little initiative to explore new methods or propose novel hypotheses, which limits the development of their creativity and independent learning abilities. Moreover, the emphasis on the format and content norms of the experimental report may lead students to focus more on meeting formal requirements, neglecting the in-depth analysis and critical thinking needed behind the report. In addition to the lack of diversity in assessment methods, the current evaluation system also suffers from issues of untimely and insufficient feedback. Comprehensive experiment assessments are typically conducted after the experiment has concluded, with grades assigned in a delayed manner. This lag in feedback prevents students from identifying and correcting mistakes in real-time, ultimately affecting both the experimental outcomes and the overall learning experience.

3. Comprehensive Experiment Teaching Reform Measures

3.1 Design of comprehensive experiment teaching processes

Before the experiment, the teaching team guides students in reviewing scientific literature related to the experimental theme through specialized lectures or seminars. This allows students to understand the latest technological developments. Based on the reviewed literature and existing experimental foundations, students propose experimental plans which are validated and optimized through group discussions and instructor feedback. For instance, in the comprehensive experiment on "Heat Treatment and Properties of Metallic Materials," students review relevant literature to understand how different heat treatment processes affect the microstructure and properties of metallic materials, as well as related research findings and cutting-edge technologies. Students work in teams to write a literature review, summarize the current state of research and proposing their hypotheses and improvement ideas for the experiment. Based on the information gathered from the literature, students independently design detailed experimental plans, select parameters such as temperature, holding time, and cooling rate, and predict the trends in material properties. The teaching members organize group discussions to evaluate these experimental plans, allowing students to optimize their plans through peer interaction. By closely integrating literature review with experimental design, students can better understand the application of theoretical knowledge in practical operations, thereby enhancing their research skills and fostering their practical innovation capabilities.

During the experimental teaching process, a dedicated data analysis module is introduced to help students utilize data processing software such as Origin and MATLAB for data visualization and statistical analysis. Students are encouraged not only to describe the data but also to deeply consider the underlying physical significance and mechanisms influencing the data. By posing open-ended questions, students are guided to reflect on whether the experimental results align with expectations and to analyze any discrepancies. For the experiment report writing, students are required to strictly follow scientific research standards in summarizing conclusions and to provide a detailed justification process.

Outside the classroom, the teaching team actively encourages students to participate in high-level academic competitions, such as the National Mechanical Innovation Design Competition, the National College Students Advanced Mapping Technology and Product Information Modeling Innovation Competition, the National Metallography Competition, and the National Casting Process Design Competition. These competitions comprehensively enhance students' engineering practice skills, technological innovation abilities, and teamwork spirit, laying a solid foundation for their future career development.

3.2 Integration of virtual and physical teaching resources

To address the challenges posed by slow updates and insufficient quantities of experimental equipment, the teaching team actively applies for laboratory construction projects to acquire essential instruments and equipment that are urgently needed for comprehensive professional experiments. Additionally, collaborative laboratories and training bases are established with partner enterprises to ensure the necessary hardware support for experiments. On the other hand, the teaching team is also focused on developing and utilizing shared virtual simulation experimental teaching resources, in order to effectively overcome many limitations of real experimental environments and enhance the depth and breadth of comprehensive experiments. For example, materials heat treatment simulation software like Thermo-Calc and JMatPro is used to demonstrate the microstructural evolution of different metals during heat treatment processes. By inputting parameters such as heating temperature, holding time, and cooling rate, students can observe changes in grain size and phase transformation under various conditions. Moreover, virtual simulation experiments such as virtual disassembly and assembly of injection molds, stamping molds, virtual mold manufacturing, forging defect analysis, and process simulation are developed. These virtual experiments allow students to repeatedly practice experimental operations in a safe and controlled environment, which can reduce the consumption of actual materials and the wear and tear on equipment, enabling them to explore different experimental designs and optimization strategies. Integration of virtual simulation technology with actual experimental operations can leverage the unique advantages of modern information technology in higher education, significantly enhancing students' engineering practice and innovation abilities.

3.3 Building a dual-qualified teaching team

Through a collaborative mechanism between universities and enterprises, efforts are made to build a dual-qualified teaching team with both teaching and practical industry expertise. This initiative aims to establish interdisciplinary and cross-domain course teaching teams, fostering students' ability to think critically and solve complex problems using multidisciplinary knowledge. First, based on the Mechanical Engineering Alliance established by the School of Mechanical Engineering, experienced industry experts from the materials forming and control sector are recruited as part-time instructors. These experts systematically integrate industry demands, technical standards, and real engineering cases into the experimental course teaching framework, providing students with direct insights into the current state and future trends of the industry. Secondly, the research strengths of the Shandong Institute of Mechanical Design are fully utilized to attract research experts with strong backgrounds in the materials forming and control field to join the teaching team. These experts bring cutting-edge scientific research and the latest advancements into the classroom, offering students the opportunity to engage with the latest research developments in the MFC domain. Finally, the teaching team continuously enhances their professional capabilities and teaching effectiveness by participating in teaching seminars, encouraging educational research, writing teaching research papers, and applying for educational research projects. Through these activities, the teaching team stays updated with the latest teaching methodologies and research outcomes, to ensure ongoing improvement in the quality of experimental teaching.

3.4 Establishment of OBE-based comprehensive assessment system

In accordance with the standards for engineering education accreditation, an Outcome-Based Education (OBE) assessment and evaluation system is developed for comprehensive professional experiments. This system integrates formative and summative assessments, as well as qualitative and quantitative evaluations, to comprehensively measure the experimental skills, innovation capabilities, ability to apply knowledge, and teamwork and communication skills of students. Formative assessment is embedded throughout the entire experimental process, covering various aspects such as literature review, experimental design, data recording, and analysis. This approach ensures that students receive timely feedback and guidance at every stage of the experiment. Summative assessment focuses on the writing and defense of the experimental report, providing a holistic evaluation of students' overall performance through a combination of quantitative and qualitative methods. This multidimensional evaluation system not only enhances the experimental proficiency and innovative capabilities of students, but also encourages the development of a rigorous and scientific learning attitude. Additionally, it fosters teamwork and communication skills, which are crucial for their future professional careers.

4. Outcomes of the Comprehensive Experiment Teaching Reform

The new comprehensive experiment teaching reform and practice system has been implemented in Qilu University of Technology since 2018, with the aim of cultivating innovation and practical abilities of students majored in the Materials Forming and Control Engineering. Nearly 1000 students have benefited from this initiative, and the teaching effectiveness has received high praise from students. Students have generally reported significant improvements in their engineering literacy and overall competence through this reform, providing a solid foundation for addressing complex engineering problems in practice. Additionally, it has actively promoted the dissemination of the reform's outcomes. In recent years, the textbook Materials Forming Processes-Welding and more than 10 papers have been published, and more than 30 national-level awards in competitions such as the National Metallography Skills Competition have been won by students. These achievements highlight the success of the reform in enhancing the quality of education and underscore its impact on both student development and academic contributions.

5. Conclusions

Through the systematic reform and practice of comprehensive experimental teaching in the Materials Forming and Control Engineering major, Qilu University of Technology has achieved significant success in enhancing engineering practice skills and technological innovation capabilities of students. The reformed teaching system places greater emphasis on the design and implementation of comprehensive experiment courses, optimizing the allocation of teaching resources and faculty development. Additionally, a scientifically sound evaluation system has been established, which has greatly improved students' ability to tackle complex engineering problems. The results demonstrate that this teaching reform has not only effectively strengthened the practical and innovative abilities of students, but has also enabled them to achieve outstanding results in various technological innovation competitions. This experience provides valuable insights and references for teaching reform in other related disciplines.

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