Development of a Project-based Plastic Injection Molding Course for Manufacturing Programs

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Abstract

Bradley University plays an important role in educating ABET accredited manufacturing engineers to major industries, such as Caterpillar or John Deere nearby. In recent years, our constituencies have voiced that plastics product design and injection molding process be considered key competences in our manufacturing curriculum. It's always crucial and beneficial for plastics engineers to understand the whole picture of plastics product development, from the product conceptual design to the product validation. Therefore, the curriculum is structured around this goal with (1) seventeen lectures covering the fundamental theories of plastic materials, design principles such as design for manufacturing (DFM) and design for assembly (DFA), injection molding technologies, etc., (2) computer aided design (CAD), computer aided engineering (CAE), computer aided manufacturing (CAM), and injection molding lab sessions, and (3) hands-on four-module projects where students can apply the learned knowledge and go through each step of injection molded product development. The four-module project includes the injection molded plastic part design module, the Moldflow simulation module, the mold design and fabrication module, and the injection molding module. To enhance students' communication, collaboration, and project management skills, 4-5 students, as one group, are required to complete the project that requires many different skills such as design, computer simulation, CNC machining, injection molding, etc. After a year of implementation, evidence demonstrates that the program effectively enhances students' understanding and capability of plastic product development. By implementing this new curriculum, Bradley University has been able to have a higher impact on the career preparation of the students and the supply of trained plastics engineers to local industries. The presentation will illustrate the plastics injection molding curriculum and describe one of the successful four-module projects conducted based on the curriculum. The impact to students, industries, and the faculty will also be discussed.

1. Background and Introduction

1.1 Motivation for developing a plastics injection molding course

As a mid-sized private regional university, Bradley University (BU) plays an important role in educating ABETS accredited manufacturing engineers to major industries, such as Caterpillar or

John Deere nearby. Our manufacturing curriculum is focused on metals and their different processes. However, plastics, as one of four engineering materials (i.e., metals, ceramics, plastics, composites), have been widely used in all industries. Their yearly consumption has surpassed the other three [1]. To meet the industry megatrend, our constituencies in recent years have voiced that plastics product design and injection molding process be considered key competences in our manufacturing curriculum. Under such circumstance, a plastic injection molding course was developed and offered in the Spring semester of 2016, to expand students' experiential learning, enhance students' competitiveness and meet the industrial growing needs for plastics engineering professionals.

1.2 Learning objectives of the plastic injection molding course

Developing a new course starts from asking the question: "What do I want my students to learn from the course?" The goal is to help students to enter the field of plastics injection molding quickly with the fundamental knowledge base and necessary hands-on skills. The specific objectives of this course are:

- To understand plastic materials (basic resins, structures, physical, mechanical and thermal properties).
- To become familiar with a variety of plastics processing technologies
- To understand injection molding process, material selection, and the structure and functions of an injection molding machine
- To understand injection molded plastic part design and be able to apply 3D modeling and 2D engineering drawing
- To be able to use Moldflow simulation software to improve part design through a variety of analyses such as cooling analysis, gate location, warpage, etc.
- To develop skills for mold design, generate toolpath (CNC codes) in Mastercam, and complete mold fabrication on a CNC milling machine with the codes
- To develop skills for injection molding process parameters setup and optimization
- To understand the common defects of injection molding and develop troubleshooting knowledge and skills
- To understand a variety of advanced molding technologies (over-molding, gas-assisted molding, foam injection molding, micro-injection molding, co-injection molding, insert molding, etc.)
- To provide students with an appreciation of problems and perspectives in environmental, life cycle and recycling aspects of plastics use.

1.3 Course design to achieve the learning objectives

In the literature, learner background knowledge was found to have a significant influence on learning outcomes [2-5]. Depaolo et al [3] concluded a positive relationship between student background knowledge and learning outcome in business statistics and calculus, and their results revealed that the students without background knowledge in calculus had negative attitudes and poor exam performance. Hailikari et al [4] studied the relationship between student background knowledge and achievement in an introductory chemistry course, and their results demonstrated that the students who had a deeper level of background knowledge were more likely to finish the course successfully with higher final grades. Before taking this course, our students have little background knowledge in plastics and plastics processing, as our manufacturing program has not offered plastics related courses yet. Our students have background knowledge in CAD design, and machining, which is very helpful to succeed in this course. One of the challenges for the course design is how to deliver the fundamental plastics knowledge of plastics quickly within a 16-week semester. Another challenge is that there is no appropriate textbook available to cover the topics.

This three-credit plastics injection molding course, which is comprised of the following items:

(1) Seventeen 75-minute lectures for learning the fundamental theory and principles of plastic materials, characteristics of plastic part design, materials selection, design for manufacturing (DFM) and design for assembly (DFA),

(2) One 75-minute CAD modeling lab session for re-sharpening the 3D modeling skills students learned from previous course, and for applying plastic part design principles (uniform thin wall, draft angle, etc.) to the parts

(3) Two 75-minute simulation lab sessions for learning the commercial software Moldflow, to implement all sorts of analyses such as gate location analysis, molding window analysis, fill/pack analysis, cooling analysis, etc., to ensure the designed parts have a good mold-ability.

(4) Two 90-minute injection molding lab sessions for learning injection molding machine operation, parameter settings, mold installation and alignment, etc.

The sequence of learning is important. Students usually need to know some course content before they can move to another advanced topic or start another project stage. The lectures and lab sessions are arranged based on the requirements of the four-stage project mentioned below, which would help students acquire knowledge and have the opportunity to apply at the right timing.

1.4 Assessing students' learning with hands-on project, homework assignments, and exams

Project-based learning (PBL) is a student-centered pedagogy, and it involves a dynamic classroom approach in which students obtain a deeper knowledge through active exploration of real-world challenges and problems [6]. PBL is particularly helpful for engineering students. Students learn about a subject by working for an extended period of time to investigate on a complex question, challenge, or problem [6]. Therefore, a four-stage project is required for students to develop an injection molded product, which starts from product conceptual design, developing detailed 3D models and 2D engineering drawing, conducting Moldflow simulation to improve the design, applying Mastercam to generate CNC tool path for mold fabrication, installing the mold and machine setup, fabricating the parts, inspecting the quality, and writing a self-reflection report to summarize the learning and analyze how to improve the quality and eliminate molding defects with what students learned from troubleshooting techniques in classroom. This project reflects the entire cycle of injection molded part development, so that students will have a whole picture on how plastics parts are made from customer needs to market. Apart from the hands-on project, ten homework assignments and two exams are used for assessing students' learning outcome. As shown in Figure 1, the project contains the following stages:

(1) Stage 1: Injection molded plastic part design

(2) Stage 2: Moldflow simulation of designed parts

(3) Stage 3: Mold design and fabrication with a CNC milling center

(4) Stage 4: Injection molding of designed parts

The organization of this paper is as follows: This project-based plastics injection molding curriculum model will be demonstrated in the next section, followed by a case study of a student team project conducted. Finally, conclusions and discussions of future curriculum improvement strategies will be presented.

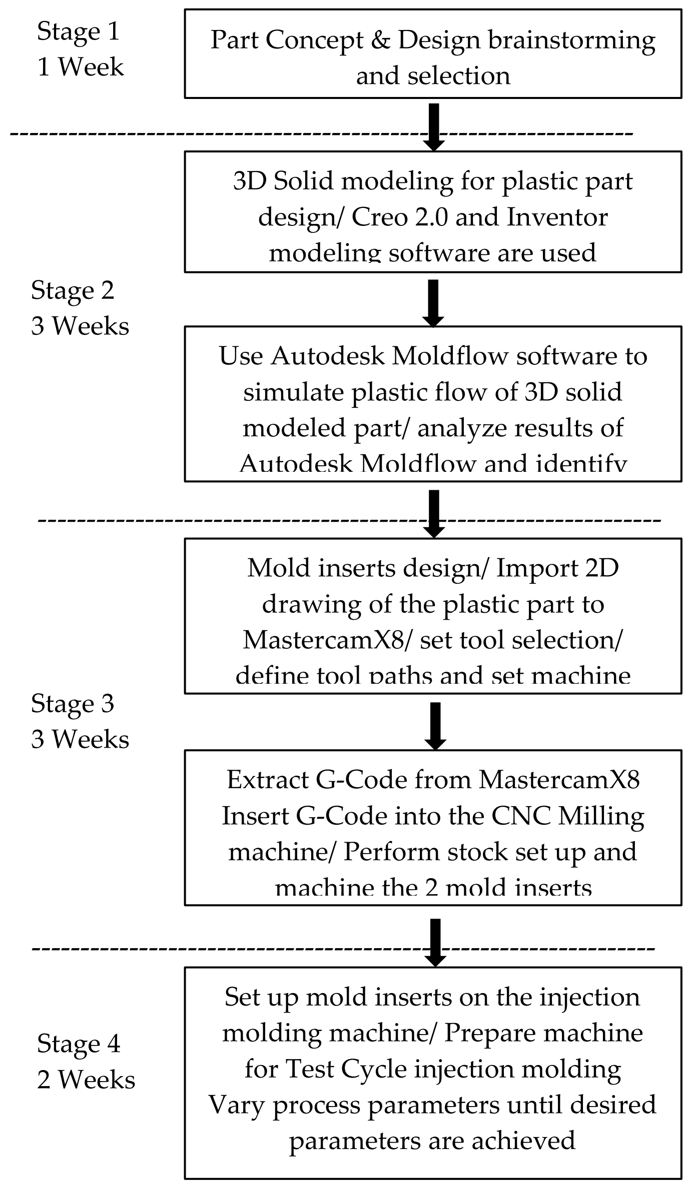

Figure 1. Four-Stage Project of Injection Molded Part Development

2. Overview of Injection Molding Project

The purpose of the project is to encourage students to apply the knowledge and theory learned in classroom, to develop an injection molded plastic part. Through the project, students got trained in the entire product development stages for injection moldings. They were able to integrate a wide range of knowledge and skills to complete the project, including but not limited to part conceptual design, 3D modeling and 2D engineering drawing development, Moldflow simulation, tooling design, CNC toolpath generation in Mastercam, molding machine setup and parameter optimization, and fabrication. To enhance students' communication and collaboration skills, they were grouped together and each group had 4-5 students. To be creative, they are given complete freedom to either design a new plastic part or modify an existing plastic part. The outcome of the project is summarized in the following.

Stage 1: Injection Molded Plastic Product Design

Before the beginning of Stage 1, the powerful Axiomatic Design tool was introduced to students [7]. Design is an interplay between what we want to achieve and how we achieve them. It is basically a mapping process among four domains, as shown Figure 2. It is expected that this important concept was rooted into students' brain – every design starts from the customer needs. The conceptual design is a mapping process between the functional requirements of the product and the customer needs [7].

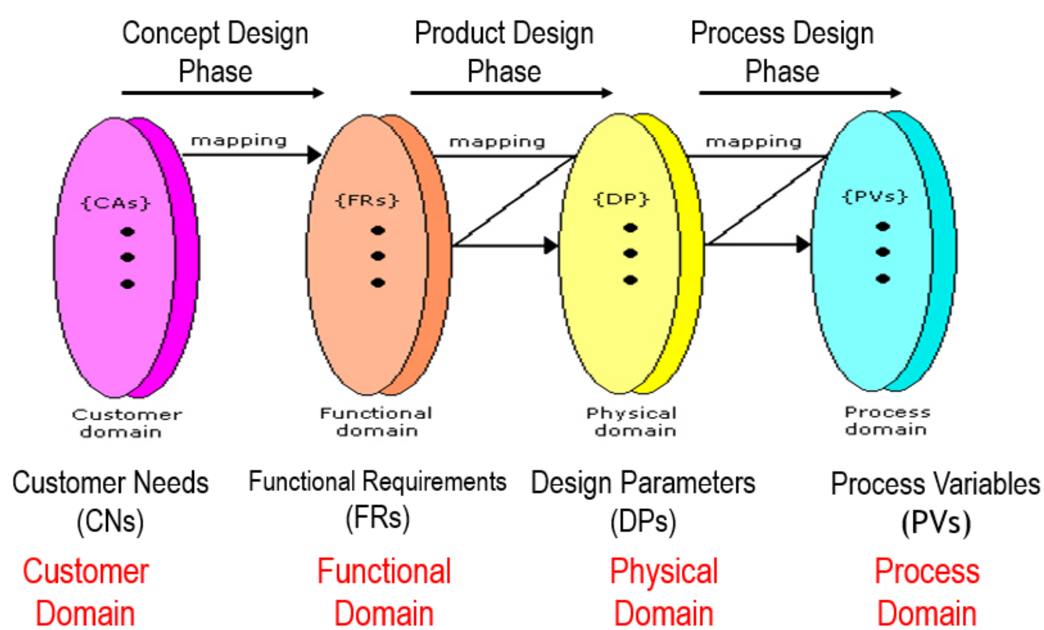

Figure 2: Four Domains for Design Mapping

Apart from learning the Axiomatic Design tool, the students learned the plastic part design principles, DFM (design for manufacturing) and DFA (design for assembly), in the classroom.

These principles include uniform wall thickness, cooling time estimation, draft angle for part ejection, reinforcing rib design, boss and gusset design, undercut, smooth transition at corners, snap-fit design, hinge design, etc. These principles are critical to the design of injection molded parts. For example, if draft angles or undercut was not taken into consideration, part ejection issues would occur during processing. Other important concepts such as uniform part thickness, shrinkage calculation, warpage issues and causes, were delivered with classroom lectures, so that students can apply these concepts and principles to their design, to avoid costly mistakes.

After grasping these important design principles and concepts, the injection molding student team collaborated to develop a conceptual design. This activity allowed the student team to gather information about the constraints and limitations of the injection molding machine, such as shot capacity and clamping tonnage. Based on the collected information, the student team was able to conceptualize the part they wanted to fabricate. After coming up with the basic idea, the student team then had to brainstorm how to design the part considering certain attributes associated with injection molded parts such as shrinkage and warpage. This is especially important because misinformation can lead to a defect. Taking all this information into account, the student team was able to create a 3D model and a 2D engineering drawing of the plastic wrench, as shown in Figure 3. The wrench is designed to function as a removing tool for 3/8" a hex cap. It is small and lightweight to fit comfortably, but will function at the light workloads. The part thickness will allow for flexibility in the non-functional direction but remain relatively rigid under use. The raised text will allow for more grip and an easy identification means which is designed to last for the lifetime of the part

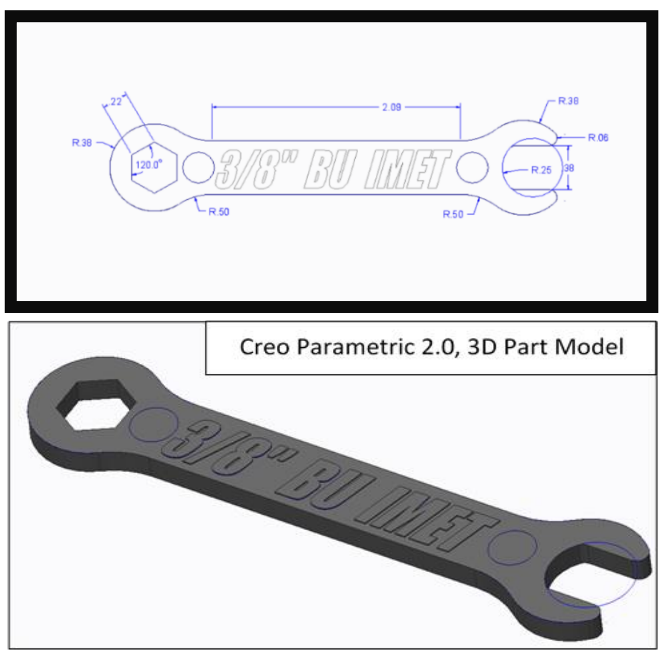

Figure 3. 3D Model and 2D Engineering Drawing of a Plastic Wrench

Stage 2: Moldflow Simulation

Moldflow Simulation Adviser is a commercial powerful software that provide simulation tools for injection mold design, plastic part design, and the injection molding design process. It has many functions that can be used to determine the mold-ability of designed part and help improve the design. It is widely used in injection molding industry. Through two 75-minute simulation lab sessions on Moldflow, students were able to grasp the basic skills and conduct the fundamental analyses, such as gate location analysis, cavity filling analysis, packing analysis, sink mark analysis, warpage analysis, and molding window analysis. After importing 3D part models, the program simulates the flow behavior of the plastic material during the molding process, and provides you with important data such as cycle time, if the mold will fill, and where defects are likely to occur. Through simulation setup and result interpretation, the student team was able to see how changes in materials, geometry, and gate location can affect the manufacturability of their designed part. Upon reviewing the results of the simulation, the student team was able to optimize their design and run the simulation again with their redesigned part. Performing such simulation analyses enables students to improve their design and verify the mold-ability of the part.

Stage 3: Mold Design and Fabrication

Once finalizing the part design with the mold-ability verification of Moldflow simulation, the student team was able to use Mastercam (i.e., computer aided manufacturing software) to create the CNC G-codes to cut the mold inserts. Mastercam is the most widely used CAD/CAM software package in the world. It has a comprehensive set of predefined toolpaths—including contour, drill, pocketing, face, peel mill, engraving, etc. Mastercam enables machinists to cut parts efficiently and accurately. In the prerequisite course, students already learned Mastercam programming. This project gives them an opportunity to refresh and apply Mastercam skills to cut a real aluminum mold. Different cutting tools (endmill, ball endmill, and engraving tools for machining) were selected and used to cut the mold cavity in a Haas CNC Vertical Machine Center. Figure 4 shows the toolpath generated by Mastercam and the associated G-codes will be transferred to the Haas CNC milling machine to cut the mold inserts.

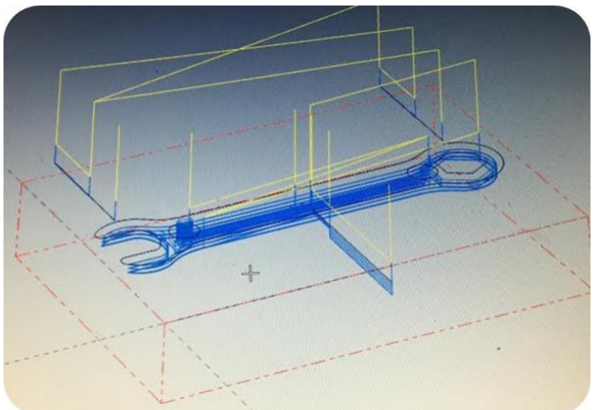

Figure 4. Toolpath and G-codes Generated in Mastercam

Mastercam also allows users to visualize what their mold will look like based on the tools and toolpaths they choose. A visualization of the toolpath used in Mastercam is shown in Figure 5.

Figure 5. Toolpath and G-codes Generated in Mastercam

Figure 6 shows that the mold insert was being cut on the Haas CNC milling machine with G-codes generated by Mastercam. The fabricated mold inserts are shown in Figure 6.

In this stage, the student team was able to apply Mastercam programming skills and CNC hands-on machining skills to make their mold inserts, which would be used in the next stage.

Figure 6. HAAS CNC Milling Machine Was Used by Students to Cut the Mold

Stage 4: Injection Molding of Designed Parts

Figure 7 shows that an ENGEL E-victory 30 injection molding machine was used to train students and help them to complete their projects. Two 90-minute injection molding lab sessions were offered for students to learn the basic operation of the injection molding machine, molding parameter settings, mold installation and alignment. After the training, the student team was able to use the machine independently to complete their project.

Before using the machine, the student team had to review data provided in the lectures and by their Moldflow Simulation analyses, so that they could set up the injection molding machine correctly. Figure 8 shows the mold insert installation, alignment and setup. To set up the proper molding parameters, a gate seal study was conducted. The first several parts which were produced with the mold revealed some flash defects, but the defect was resolved by slightly adjusting molding parameters such as injection speed and shot size. The vents located on the mold properly served their purpose and performed well, which resulted in a very well packed/molded part with uniform geometry, no defects, and great quality. The team then tested varying shot sizes, clamp forces, cooling times, and injection speeds to determine the optimal parameters for producing their part. Figure 9 shows one of injection molded parts the team produced.

Figure 7. ENGEL E-victory 30 Injection Molding Machine Used in Training and Project Completion

During this stage, students learned mold installation, alignment, and setup. They were able to set up the proper molding parameters based on their Moldflow simulation results (i.e., molding window) and a gate seal study. The common molding defects and their root causes were introduced in the classroom lectures. Students were able to apply the knowledge to analyze and resolve the defect issues. Hereby, some troubleshooting skills were developed to eliminate molding defects, based on the lectures and hands-on practice.

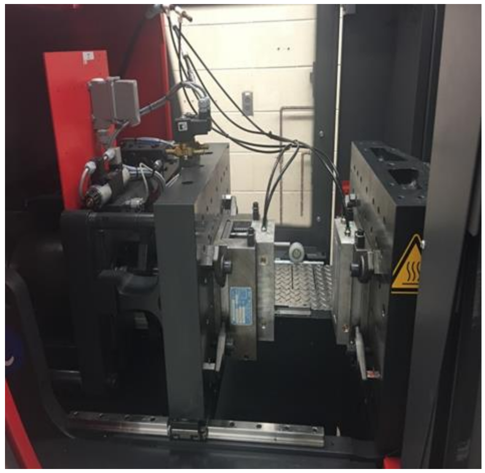

Figure 8. Mold Insert Installation, Alignment and Setup

Figure 9. Injection Molded Plastic Wrench

3. Reflections on the plastics injection molding course

In addition to the team project results, each student is required to submit an essay discussing about what he or she learned through the plastics injection molding project. Everyone enrolled in the course stated that the plastics part molding project is the greatest way of applying the principles and concepts learned in the classroom, and they learned most from the project. Some of the students' comments are shown in Table 1.

Table 1. Comments from Students about the Plastics Injection Molding Project

1	The plastic injection mold project was very interesting as well as entertaining. It challenged us to apply the knowledge that we've gained throughout the duration of the course
2	The best part about this class I believe is the plastics molding project. This made me apply many of the principles that I learned throughout the semester. Everything from part design and mold design, to packing time analysis.
3	This course has showed me how many steps it takes to design molds even for the smallest simple parts. I have also learned the use of mold flow analysis to streamline the mold design process.
4	Overall I have learned a lot about injection molding through the course project. I would recommend this course to future students. In the past no class touched upon injection molding which is major part of the manufacturing industry.
5	I learned about common defects of injection molding parts. This helped us with our injection molding project because we understood what settings should change if certain events were to happen. For example, if our part did not fill all the way, we would know we should change the injection pressure or shot size.
6	I learned a lot of information during the course of this semester about injection molding, polymer science, Moldflow Advisor, and design. I really enjoyed being able to apply all of these concepts during the group project and also using Moldflow.
7	After this project I have learned a tremendous amount and feel confident in my abilities and knowledge of the injection molding process to be able to: design parts for moldability, design mold cavities and runner systems, operate an injection machine, as well as, identify and remedy part defects as the present themselves.

It seems that this hands-on project based injection molding course was successful for the past two semesters it offered. The 4-stage projects completed demonstrate the skills and knowledge the students acquired from this course. Although the injection molded parts typically were pretty simple, it is very important for students to go through each step of injection molded part development and understand the whole picture. The plastic parts that the students designed and fabricated are the first piece they molded in their life time, which excited and inspired most of students.

Some local injection molding companies were glad that Bradley University started to develop plastics education curriculum, and provided strong support one way or another, to further development of plastics education. The CEO at an injection molding company stated in his email: "The reason we are promoting enhanced plastic education at Bradley is that we estimate that 60% of the built world is made of plastic. Yet 99% of the engineering schools in the United

States teach no plastics manufacturing or plastic product design". We are pretty sure that collaboration with local companies will provide more opportunities for students and promote the plastics education at Bradley.

The course was developed and offered in the Department of Industrial and Manufacturing Engineering & Technology at Bradley University Peoria, IL, and demonstrated an initial success. The Department of Mechanical Engineering at its institution also would like to strengthen its plastics education to their students which enhances inter-departmental collaborating opportunities.

4. Conclusions and Future Improvement

The presented plastics injection molding curriculum provides a benefit to students and leads them to the field of plastics processing. The well-designed four-stage project gives students an opportunity to apply what they have learned from classroom lectures, as well as previous knowledge and skills, to complete the hands-on projects. The sequence of lectures and lab sessions was arranged in a way so that students had necessary knowledge and skills to complete each stage of their project, and in turn it reinforced and enhanced what they learned. The course content is very large, covering a wide range of topics related to plastics injection molding. This seems to be excellent to those capable students who have a strong background. However, it probably overwhelmed the students with little background. How to reduce the course content and keep the essential lectures would be the future topic for course improvement.

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