Tool Design and Concurrent Engineering using Rapid Tooling Construction Methods

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Abstract

Prior to rapid prototyping (RP), the depth to which students could analyze a design, product or process was limited due to the length of the academic quarter. Now, the Manufacturing Engineering Technology curriculum is able to further incorporate design, production, and testing in concurrent engineering and student projects. This paper discusses new developments in a Tooling for Plastics Processing course that focuses on the design and construction of injection molding tooling where the students investigated several methods of creating prototype tooling from RP models. Each method was evaluated for tool and part characteristics including surface finish, cycle time, cost, repeatability, and tool longevity. These methods can also be utilized in subsequent courses to create tooling and manufacture parts for design analysis and testing. Using RP, students are now better able to perform multiple iterations of production and testing of advancing designs using RP. The level of learning that occurs is dependent on two main things: how much iteration occurs and how well the results are analyzed and utilized in the next or concurrent step.

1. Introduction

Rapid Prototyping (RP) is a method of fabricating a model directly from a solid modeling software or CAD file. RP technologies like Stereolithography (SLA), Selective Laser Sintering (SLS), and Fused Deposition Modeling (FDM) deposit thermoplastic powders or resins in thin layers to construct the model[1]. Designs for small parts can go from a CAD file to an actual model in just a few hours. The Engineering Technology department at Western Washington University recently completed a solid modeling lab and purchased rapid prototyping equipment with a Concurrent Engineering Grant from an industrial partner. Concurrent engineering practices are now being developed at all levels of the curriculum.

In the plastics industry, concurrent engineering is very important due to the high cost of tooling and long lead times. Typically, concurrent engineering is utilized by manufacturing prototype tooling early in the design phase to analyze and adjust the design. Production tooling is manufactured as the final step. Beginning Winter quarter of 2000, the Tooling for Plastics Processing course incorporated similar concurrent engineering practices. The students in the class were divided into teams. Each team chose a simple part design and a prototype mold construction method. Each prototype mold construction method uses a rapid prototyped model to create the mold. The RP models were created using the department's FDM machine. After completing the prototype molds, parts were manufactured using injection molding. After part analysis, the students updated the part design and the tool design. Then a machined aluminum mold was produced using the new design to manufacture additional parts. Parts from the prototype tool and the machined tools were evaluated and compared. The results from each team were compiled and a comparison of the construction methods was completed.

2. Role of Rapid Prototyping and Prototype Tooling in the Curriculum

Producing rapid prototype models for evaluation and testing is a topic of great interest in many manufacturing industries. The increase in RP technologies in the past decade has allowed manufacturers to create RP parts that closely resemble the final part. These parts may then be used for fit and functionality testing. The quantitative testing of an RP model is very limited when the effect of the manufacturing process on the part needs to be evaluated This includes such effects as material shrinkage, dimensional accuracy, and anisotropic orientation of the material or when the design material is different from the RP model material.

When the success of production tooling depends on the accuracy of these tests, the parts that are being tested must be of the design material and manufactured in a process that closely resembles the final production process. To lower the risk associated with construction of production tooling, the plastics industry is employing prototype tooling to manufacture parts for evaluation and testing[2,3]. One method of constructing prototype tooling is simply casting aluminum-filled epoxy over an RP model. To ensure that the parts produced from prototype tooling closely resemble the final production part, much research is being performed to compare RP tooling to machined steel tooling. In recent research, the properties of parts produced in an RP epoxy tool were within 10-30% of parts produced in a steel tool[4].

Prior to the arrival of rapid prototyping equipment in the department, the laboratory portion of the course focused on the construction of tooling, using manual and CNC machining. Sometimes students only partially completed the assignment due to complications during manufacturing of the tool. These complications were usually attributed to the part design, the tool design, or the machining program. With this method of construction, there is generally not enough time, machining resources, or operating budget for a second attempt.

Using RP models to speed the process of creating tooling has three distinct advantages over the traditional method of machining. The first is that the students get laboratory experience in the design and construction of tooling with a shortened time requirement. This allows for students to make two design iterations before the end of the quarter. The first part design is manufactured using a prototype mold, and the redesign is manufactured using a machined mold. This methodology closely resembles the design process that is used in industry. Due to the advances in rapid tooling, many plastic part manufacturers create prototype tooling to evaluate a design prior to machining the production tooling. One of the major benefits of concurrent engineering is the ability to uncover design defects early in the design process. The cost incurred to correct a design flaw realized in the early stages is a fraction of the cost of a defect that gets incorporated into the final tooling. With the cost of production tooling for injection molding ranging from $10,000 to $250,000 per mold, a prototype tool is a wise investment. Therefore, the second advantage is that knowledge of prototype tool construction processes is becoming a necessity in an industry that has an ever-increasing dependence on rapid tooling technology. The third reason is due to the decreased cost, construction complexity, and equipment requirements of prototype tooling. With the traditional method of machining, only students in the CNC or

Tooling courses have adequate access to equipment and faculty to build molds. Now, students who have completed the Tooling class will be able to build tooling to manufacture parts in subsequent courses in the department without the dependence on CNC machining equipment.

The reduced time and equipment requirement of the prototype mold construction methods can be used for many other courses in the Engineering Technology department. In addition to Senior Project and undergraduate research projects, prototype tooling can be utilized in the Plastic Product Design, Computer Integrated Manufacturing, Foundry and Forming courses.

The Plastic Product Design course focuses on the aspects of design that are particular to parts manufactured with the primary production processes, specifically injection molding. The course focuses on injection molding because it is the process that allows for the most design freedom. Therefore design practices learned are easily translated to other plastics processes. In the laboratory portion of the Plastic Product Design course, the students design products and fabricate models to evaluate the performance characteristics by physical and thermal testing. Often, these models do not function like the designed part would due to the disparity in manufacturing methods and material used. Most models are fabricated by casting, thermoforming, or machining. Parts manufactured by injection molding will look and function different than these fabricated models. Even RP models do not perform well due to the layered structure of RP methods. RP processes deposit thermoplastic powders or resins in thin layers to build a part. The edges of the stacked layers create a rough or stair-stepped surface. The properties of RP parts are also non-homogeneous due to the layering. In addition, the choice of materials used to build RP parts is very limited. The students' ability to construct prototype molds will allow them to properly evaluate their designs because the part was manufactured using the correct material and the same process as the final production process.

In addition to many other topics, the Computer Integrated Manufacturing course gives students an introduction to Finite Element Analysis using ANSYS and Design Space. This simulation software allows a student to model a part, load it with multiple forces, and analyze the stress and strain that the part undergoes during loading. For verification of the results obtained from the FEA simulation, students can manufacture transparent parts of their design and use a polarized light to analyze the stress concentrations under loading. The transparent parts could be manufactured by injection molding resin into a mold created by prototype mold construction methods.

In the Foundry and Forming course, students are introduced to the different cast metal manufacturing methods, including investment casting. Students will be able to construct prototype molds for use with wax injection molding. Wax parts can be injection molded and then ceramic coated. These coated wax parts are placed in an oven and the wax is burned out, leaving a hollow ceramic shell. The ceramic shell is embedded in sand for support and molten metal is poured into the ceramic shells.

3. Methodology

Because the emphasis of the course was tool design and construction, the students were given a simple part design to be manufactured by injection molding. The students modeled the design using Rhino, Pro-E, or IDEAS. One facet of the tool design challenge is designing and creating a mold base that will accept cavity inserts constructed by the two different methods, prototype inserts and machined aluminum inserts. Constructing a single mold base for both sets of inserts minimized the amount of manual machining required for the project.

In concurrent engineering, the process of part design evaluation and manufacturing process evaluation leading to redesign is incorporated in many steps. The procedure followed for this course utilized that idea in many ways. The process methodology is summarized in Figure 1. Due to the dimensional changes that occurred to the design at each step of mold construction, the students measured and evaluated each component after it was produced. Adjustments were made during the process to ensure proper dimensions of the final product. After completing the prototype mold, the students injection molded parts. Parts were produced until part quality began to diminish. The students then determined the cause and proposed methods that could be used to either improve the quality of the parts or extend the life of the tool. Evaluation of the parts created with the prototype tooling allowed for modifications to the design for the next phase, machined aluminum tooling. After completing the machined aluminum inserts and assembling them into the mold base, parts were injection molded. These parts and the machined cavity were measured and evaluated.

The parts manufactured by both molds were then evaluated for surface finish, dimensional accuracy, repeatability, functionality, mechanical properties, and level of crystallinity. Students evaluated the prototype construction method and machining method on such issues as cost, complexity, and limitations. The raw material cost, labor hours, machine hours, cycle time for each part, and the total construction time were included in the cost comparison. The success of each tool was also evaluated based on the complexity of the construction method compared to the skill level of the students. The prototype mold and the machined mold limitations were then discussed. These limitations included part size and complexity, the finish of the surface, dimensional accuracy, part functionality and the total number of parts produced. A completed mold base, prototype insert, machined insert and the respective parts that were molded from each insert are shown in Figure 2.

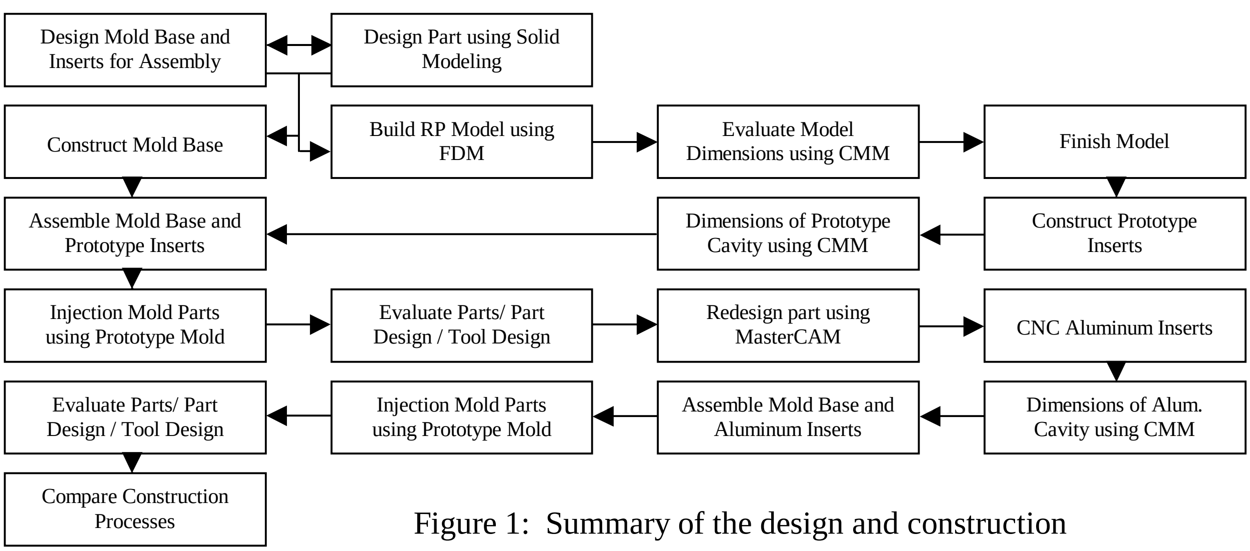

Figure 1: Summary of the design and construction

4. Prototype Mold Construction Methods

The Tooling for Plastics Processing class was divided into teams. Each team chose one construction method that best fit their part design. For the more complex designs, two RP models were created. The parting line was used to divide the part into an A-side RP model and a B-side RP model. Summary descriptions of the methods are given below. More detailed procedural information was obtained from many sources[5,6,7].

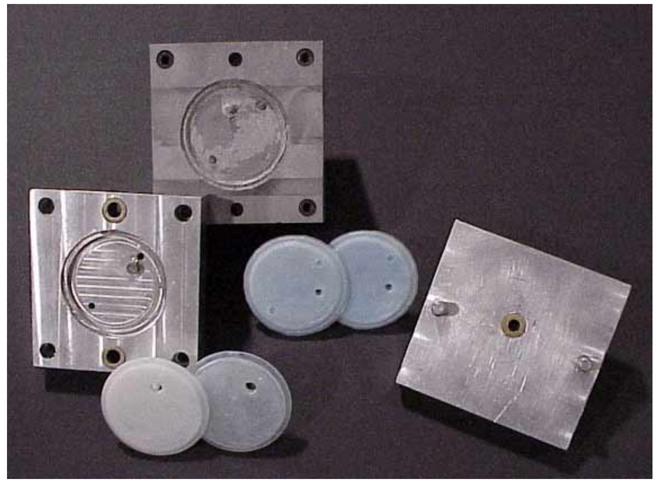

Figure 2: Completed mold base, prototype insert and machined insert with injection molded parts

Four molds were constructed by casting aluminum-filled epoxy around the RP model in the bottom of a chase. This method employed the simplest construction techniques, but was the most difficult to obtain quality parts. Figure 3 illustrates the surface roughness caused by the layers in an unfinished RP model and voids due to the epoxy. All attempts to smooth the surface of the model using primer-fillers caused off gassing and voids during the heat curing of the epoxy. Many molds had to be resurfaced with epoxy filler, as shown in Figure 4. The epoxy molds were not able to produce many injection molded parts before failure.

A more complex mold was built by creating a shell over the RP model by spraying a thin layer of zinc using metal arc spraying. A chase was built and the shell was back-filled with aluminum-filled epoxy. The surface quality and tool longevity was greatly increased over the molds made with just epoxy. Figure 5 shows the complexity of the design and the surface quality of the tool.

Figure 3: Surface of mold created by casting epoxy over unfinished RP model.

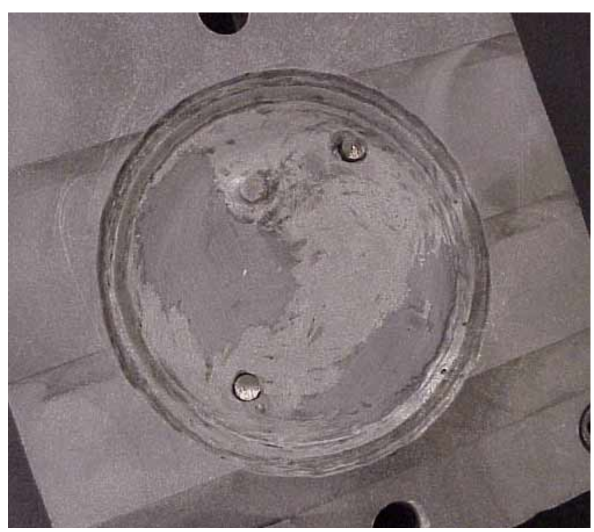

Figure 4: Patched and sanded mold surface to correct voids caused by primer.

Investment casting was also used to create two molds. Wax was cast around the RP model in a chase. The wax was coated with investment plaster and then the wax was melted out. The plaster shells were placed in sand for support and aluminum was poured in. Trapped gas and imperfections in the wax model caused cavity imperfections that were translated to the injection molded parts. The investment cast tools had the most similarities to machined aluminum tools in terms of durability, but had poor surface finish.

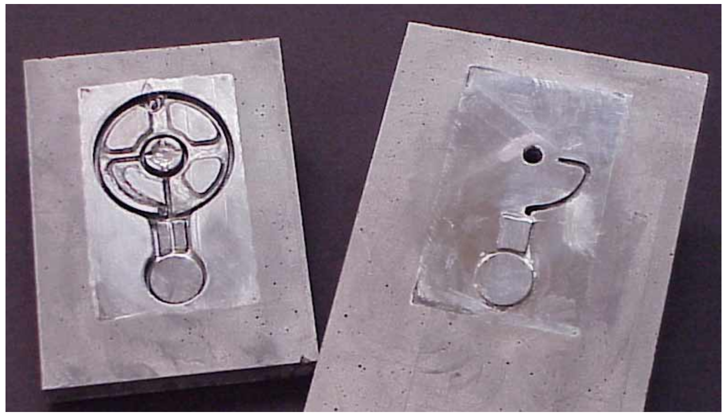

Figure 5: Mold constructed using metal arc spray and aluminum-filled epoxy.

5. Conclusion

Seven mold sets were manufactured and are shown in Figure 6 along with injection molded parts from each mold. This study revealed that metal arc spray tooling is the preferred method for mold construction of complex cavities. The investment cast molds are durable, but have poor surface finish. The epoxy molds were difficult to construct, have poor surface finish and deteriorated quickly. Further study into these methods may find ways to improve tool surface finish and longevity.

Using the results compiled from each team, students who have completed the Tooling for Plastics Processing course are better equipped to evaluate a design and determine which mold

Figure 6: Seven mold sets manufactured using traditional machining and prototype construction methods.

construction method is best suited for an application. In addition, students gained experience in mold design, construction, and evaluation. They have also gained an understanding of the use of prototype and machined tooling in the concurrent engineering design processes.

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