Teaching Composites Manufacturing Through Tooling

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Abstract: Teaching an introductory composites course can be a challenge. Variables such as material selection, tooling, processing, and configuration can make the task seem daunting to both the student and the instructor. This paper outlines a new way of looking at an introduction to composites course through the eyes of tooling. Tooling is often the last thing that is considered when designing and manufacturing a product. Having the tooling be chosen first and then designing a product around it leads the students to discover the importance of it on the quality of the product as well as what manufacturing methods are appropriate for both the tooling and the product. Turning the tooling technique into the driving factor also allows for new innovations in composite tool manufacturing to be examined and tested by the students and shared with the class.

Introduction:

Western Washington University has a unique Plastics and Composites Engineering (PCE) program that focuses not only on materials science, chemistry, and characterization, but in manufacturing as well. The PCE program offers theory and hands-on courses in traditional thermoplastic and composite processing techniques such as injection molding, extrusion, compression molding, autoclaving, and hand lay-up, as well as courses in compounding, materials characterization, and testing. The program is unique in that students are expected to understand the theory behind the materials, manufacturing, and testing processes and also be able to use that theory in the lab to manufacture, troubleshoot, test, and analyze tooling, parts, and materials [1].

PCE 372 is an introductory course into room temperature curing composite materials, manufacturing, and testing. Previously students would learn the basics of hand lay-up and resin infusion independently of tooling considerations. The students were given only one option, polyurethane foam. This led to a gap in learning and, instead of considering tooling at the beginning of a project, it was often left as an afterthought. Even then tooling was only a minor consideration as most students chose to use the method they were presented with in lab and not branch out to other methods that might have been more appropriate for their application.

Previous Course Content:

Since 2012 the content of the Introduction to Composites (PCE 372) course consisted of lecture topics, a prescribed laboratory exercise, and two projects. The lecture content covered a large variety of topics but had its focus in room temperature materials and processes. An Advanced Composites course was (and is) also part of the curriculum and focused more on classical lamination theory and elevated temperature materials and manufacturing process.

The prerequisite for the introductory course is an introduction to polymers and processing that mainly focused on the basics of polymer chemistry and thermoplastic materials. The goal of the introductory composites course is to enable the students to understand the basics of composite materials and manufacturing including the vocabulary, matrix materials, including in-depth discussions of thermosets that cure at room temperature, with an overview of metal, ceramic, thermoplastic, and thermoset matrices that cure at elevated temperatures, fiber materials, and manufacturing processes such as vacuum bagging, resin infusion, RTM, pultrusion, compression molding, and filament winding. Topics on machining of composites and tooling are also covered.

The prescribed laboratory exercise was to make two flat panels, one using vacuum bagging and one without, using the same lay-up sequence and materials. Once completed, tensile and flexural bars were then cut from the pates and tested to determine the impact that the manufacturing method had on material properties [2].

Once the prescribed laboratory exercise was completed, students began to work on the first of two projects. The first project was referred to as the mini project. The goal of the mini project was to have the students receive instruction and hands on experience with foam shaping, creating a splash, and using gel coat. Students also gained first-hand knowledge on the impact of draft angles and tool surface finish on their part. The thought was that, once the students had gained this experience they would be more effective in the second project, named the major project. This project was to create a part of their choosing while selecting and justifying the materials and manufacturing methods to do so [3], [4].

Unfortunately, the mini project had unintended consequences. First, it only gave the students hands-on experience with one tooling method (male foam tooling) and students were found to be spending an immense amount of time on non-value-added activities such as sanding and foam shaping. Second, instruction for each step (foam shaping, using surfacing agents, spraying gel coat, manufacturing a splash, and tool repair) required the use of precious lecture time for the demonstrations. Finally, the mini-project did not always help students when it came time for them to create tooling and parts for their major project as many of them did not want to create a part from a male foam tool.

Why Change? Why Focus on Tooling?:

As the faculty and staff teaching this course began to brainstorm how to remove some of the repetition in the projects, tooling became a main source of discussion. If the tool isn't correct than the part will never be. According to a tool design engineer at Janicki Industries, "a poorly designed tool transfers a cost and quality burden into every part associated [with it], even if intended for single usage [5]."

New composites tooling methods such as using dissolvable materials and additive manufacturing have recently become commonplace in industry [6], [7], [8] and the students needed to have knowledge and experience using them. Shaping foam and making a splash were no longer enough. By focusing on tooling the students can determine what the best types of manufacturing methods, parts, and materials to use are for a given method. Likewise, it also prompts students to consider available tooling methods from the start of the design process.

Lab Component Changes:

Staff and faculty worked together to brainstorm the most appropriate tooling and manufacturing methods for students to work with. The initial prescribed laboratory component of making two flat panels using two manufacturing methods was modified slightly to exchange the non-bagged lay-up with one using resin infusion. This gave the students a broader manufacturing base in which to draw from. The two projects (the mini project and the major project) were eliminated and a new project was created to ensure tooling considerations were made up front in the design process.

At the beginning of the quarter students were allowed to choose which tooling method they would like to work with in their team. A variety of options were presented including using 3D printed molds, dissolvable molds, existing parts, and soft (foam/wood) tooling. Students could also choose between creating male or female tools. Students were required to perform research on their tooling method and to propose how they would manufacture the tooling, what types of parts are most commonly made from this tooling method, the materials they would use for their parts, and how they were going to manufacture them. Teams also received individual instruction on processes such as envelope bagging and spraying gel coat as needed.

Lecture Component Changes:

Since the student teams were all using different tooling methods, the faculty led lecture on tooling types was no longer needed. Instead each team gave a presentation to the class about the specifics of their tooling methods including manufacturing, materials, design, cost, and challenges of the method.

The Project: First Offering:

Mechanics of the Project:

The first time this new project was tested the class consisted of 36 students. Teams of four were created using nine different tooling methods. Students were free to pick both their team and their tooling method from a list given to them on the first day. Deliverables during the quarter were a functional tool, a minimum of two parts with either varying materials or manufacturing processes, a presentation about the tooling method, and a final report detailing each step of the project along with rationale and lessons learned.

Available Tooling Methods:

For each of the tooling methods the students were given an envelope of 12” x 12” unless special permission was given by the lab technician or the instructor. All tools except the ceramic mandrel and dissolvable tooling must have vacuum integrity, be stiff enough not to deform under vacuum, have no sharp edges or corners that might puncture a vacuum bag, and have an appropriately sized flange in which to adhere sealant tape. Since the ceramic mandrel and the dissolvable tooling are typically used to define the inside of a part, envelope bagging could be used instead. The nine tooling methods made available to the students were:

1. Female Tool Foam
   Students were given high density polyurethane foam that they could shape by hand or with the aid of a CNC router
2. Male Tool Foam
   Students were given high density polyurethane foam to shape by hand or with the use of a CNC router. Students had the opportunity to either make a female splash from the male plug or use it directly as a male mold
3. Soluble Ceramic Mandrel
   Students were given Aquapour [9] to create a male dissolvable system. The students had several options (3D printing, plaster, wood, plastic, etc) on how to create the mold necessary to cast the ceramic material. The casting, still in its mold, was then cured in an oven. Once cured, the mold was removed and the ceramic mandrel remained for students to lay up on.
4. Existing Part Male

With this method students were encouraged to find an existing part that they would like to replicate. Like with the male foam tool students were given the option to create a splash from the existing part or lay-up directly on the existing part itself.

5. Existing Part Female
   As with the existing part male approach, students were again encouraged to find a part that they would like to replicate.
6. 3D Printed Tool Dissolvable
   For all of the 3D printed tooling students had access to LulzBot Fused Filament Fabrication (FFF) Taz 5 printers [10]. For the dissolvable tooling the students were able to print with PVA filament which dissolves in water.
7. 3D Printed Tool Male
8. 3D Printed Tool Female
   For both 3D printed male and female tooling students were given the choice to use either HIPS or PLA. Students were also able to either print one part or several smaller parts and assemble them together to create their tools.
9. Construction/Board Press
   WWU has a ski press that is available for trained students to use. With this press the students must create tooling made from MDF that's either shaped by hand or with the help of a CNC router. Although there is a template for how to assemble the critical components such as the tip/tail and rocker, students are free to create the custom features they desire.

Images of select tools and the manufacturing thereof are found in Appendix A.

Demonstrations:

In the previous version of the course faculty and staff gave many demonstrations on subjects such as foam shaping, gel coating, using a thixotrope, making a plug, making a splash, bagging a hand lay-up and how to create a part using resin infustion. All of these demonstrations were necessary since the students were only allowed to use foam for their tooling. Since the change to a variety of tooling methods, the faculty and staff gave more team-specific demonstrations for each of their needs. Students were still required, however, to attend demos on vacuum bagging and resin infustion since they still have an initial laboratory activity of performing a basic lay-up. All students are invited to the additional demonstrations but were no longer required to attend as they were before.

Meetings:

For the first offering students were asked to sign up for a tooling method on the first day of class. A week or so later each team would have the first of four meetings with the faculty and staff member. Each meeting had a specific purpose, was held outside of normal class time, and was short (only 15 minutes each) so the team needed to come prepared. The first of the meetings was to go over the research that the team had done on their tooling method. In this meeting teams reviewed the manufacturing methods and parts that were common to their tool type so that they could create tooling that was appropriate for the process that they were going to use. The second meeting occurred during the tool manufacturing phase of the project to help teams with any issues they might be having. At this meeting teams were also required to present what manufacturing methods that they were going to use to create their parts. By the third meeting the teams' tooling must have been completed and so this meeting focused on creating parts. Teams were required to come prepared with a bill of materials for creating their parts (either two manufacturing methods or two different part configurations were required). The fourth meeting occurred while the teams were manufacturing their parts. This final meeting was intended to check in with the teams to answer any questions or concerns that they had.

Presentations & Assessment:

Each team was required to give a 20 minute presentation on their tooling method to the class. This presentation took the place of the traditional lecture that was typically performed by the faculty member. Students gave suggestions as to how to best work with the method and considerations to include early in the process. They also presented where these methods were used in industry and what types of parts and manufacturing quantities are appropriate for the methods. Since each team only focused on their one tooling method, assessment was added to the final exam to test how well the rest of the class grasped each concept that was presented.

Outcomes:

At the end of the course students were given a survey to express what they liked and what needed improvement in the new project. 30 of the 36 students completed this survey. Each of the students surveyed felt that this project was a successful way to learn a new composite tooling method. Overall the class felt that the changes were beneficial and each of the tooling methods were appropriate and important to learn about; however, they did offer some critical feedback.

Students felt that choosing a tooling method on the first day was a hindrance since the vast majority of them had no information or experience with any of the methods. Instead they suggested that the methods be made available to the class prior to signing up for a method to allow students to perform some basic, preliminary research.

As far as the tooling methods were concerned, most of the students liked the variety of types but most also greatly underestimated the time it would take to create these tools. This was especially true of the students that were 3D printing. Students believed that these methods would be the simplest as they could just load a CAD file into the printer and all would be well. Students quickly learned that prints often fail, especially when the parts being printed are large and intricate. Students also failed to consider that the surface finish of a FFF printed part may not be as clean and smooth as it needed to be to serve as a composite tool.

During the presentations, students seemed to focus more on the project and less on the theory behind their tooling and manufacturing methods. Several times faculty was relied upon to add in critical areas of information such as how this is used in industry or typical production rates and durability associated with the tooling and manufacturing methods, that were missed in the student presentations. Student suggestions were to amend the grading rubric for the presentation to reflect the importance of these areas so their understanding of each method would increase.

Although the students appreciated the support and the use of gateways to keep their projects on track, they felt that four meetings were a bit excessive. They recommended that the meetings be reduced to three.

The Project: Second Offering:

The second offering of the course was much smaller, with only 20 students. Because of this, the number of tooling choices was reduced from nine to five. Students still worked in groups of four.

Lessons Learned and Changes:

As mentioned earlier, the first time that the new project was used there was little introduction to the tooling methods and the students chose their method rather blindly. To address this concern, the second offering of the class included a very brief outline of each method's pros and cons. The time frame from when the students chose their method was also changed from immediately on the first day to the second week of the quarter so students could spend a little time before committing to a method to research them a bit more.

Small changes to the project such as creating a more robust rubric for assessment and reducing the number of outside meetings from four to three were also implemented. Faculty and staff also made it a point to remind the students that, even if they believed that their method was going to be less complicated to make, that they start early just in case something goes wrong. Information was relayed regarding previous class' experience in creating the 3D printed tooling to encourage them to be proactive.

At the end of this course students were given the same survey as the previous quarter. All 20 students replied. Again, all of them felt that the project was a successful way to learn a new composites tooling method. Student feedback from this class suggested some minor changes to project meeting times during the quarter and continued refinement of the grading rubrics.

Again, assessment of student learning was included in the final exam for the course. Students performed well on the related questions and were able to demonstrate knowledge and applications of tooling methods that were not their primary area.

Conclusions:

Although class materials and projects are always evolving, this project structure has shown to enhance student learning and recognition of the importance of incorporating tooling considerations into the design process at the beginning of a project. Students overwhelmingly feel that this approach has helped them to understand the basics of the relationship between parts, materials, manufacturing, and tooling.

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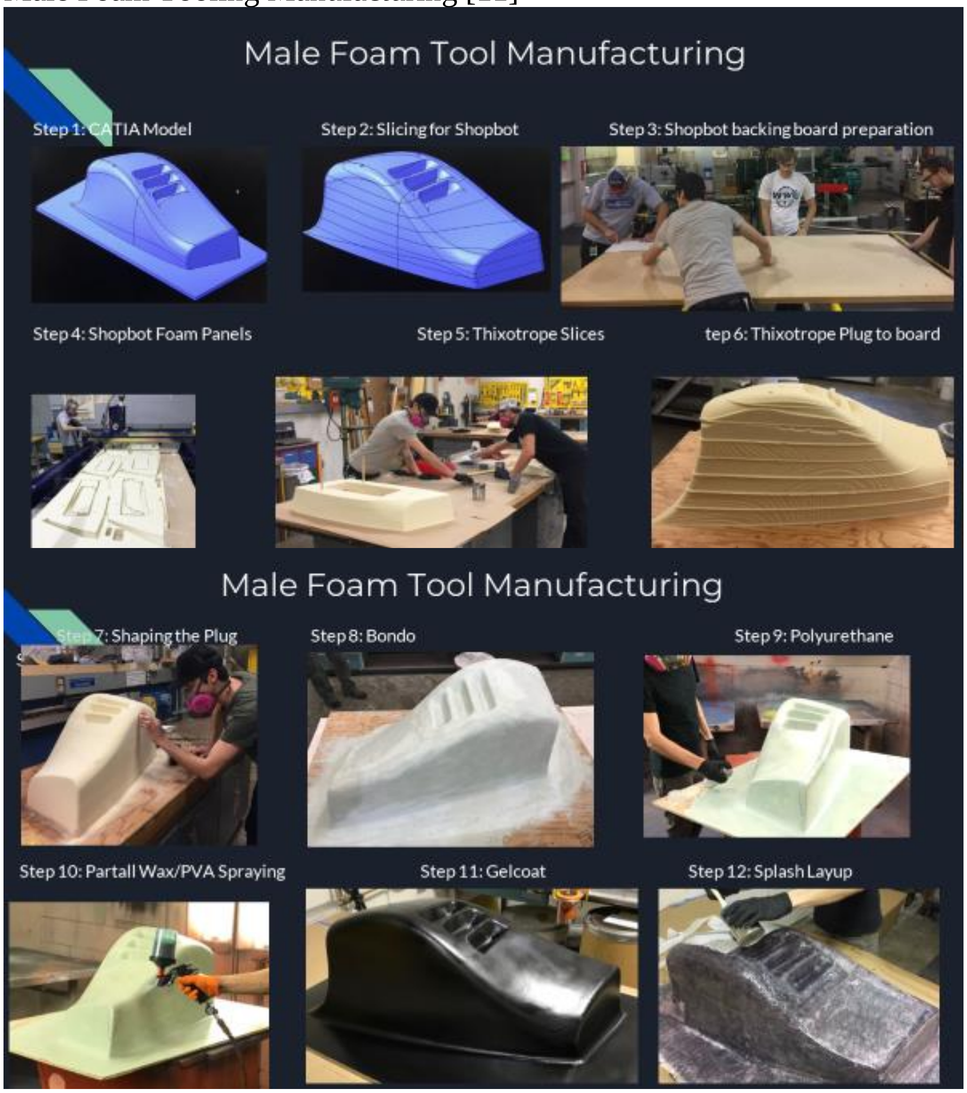
Appendix A – Tool Manufacturing and Final Products

Male Foam Tooling Manufacturing [11]



Male Foam Tool Manufacturing

Step 13: Pull the Splash

Step 14: Wet Sand

Male Foam Tool Manufacturing: Finished Product

Female Foam Tooling Manufacturing [11]

3D printed Male Tooling

3D printed Dissolvable Tooling (made with PVA)

Soluble Ceramic Mandrel Mold