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Rapid Tool Making and Tooling in Teaching Applications of 3D Printing and Additive Manufacturing

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Rapid Tool Making and Tooling in Teaching Applications of 3D Printing and Additive Manufacturing

Abstract

This paper focuses on development and teaching of rapid tool making and tooling content in the form of a 2-day workforce development workshop for a consortium sponsored by the Defense Manufacturing Communities Support Program (DMCSP) and its adaptation to college curriculum. This 2-day intensive course introduced participants to rapid tool making methods based on 3D printing. Indirect and direct rapid tooling were covered with hands-on activities including use of software tools. Tooling for multiple processes such as plastic injection molding, sand casting, room temperature vulcanization (RTV) as well as machining jig and fixture design were included in the curriculum with demonstrations or laboratory exercises. Main target audience was technical personnel from small and medium size manufacturing companies, even though it was open to similar personnel from all size of companies including start-ups. This paper presents the structure and delivery of the workshop, expected critical take-aways, involvement of multiple 3D printing and additive manufacturing processes like Binder-Jetting, Stereolithography (SLA), and Selective Laser Sintering (SLS), and the newest efforts of the author to integrate this workshop content to his rapid prototyping and reverse engineering course. The paper is concluded with possible future effort ideas, in both workforce development and engineering education fronts, also relating the latter to ABET requirements.

Introduction

This paper focuses on development and teaching of rapid tool making and tooling content in the form of a 2-day workforce development workshop for a consortium sponsored by the Defense Manufacturing Communities Support Program (DMCSP) and its adaptation to college curriculum. Indirect and direct rapid tool making and tooling were covered with hands-on activities including use of software tools. Main target audience was technical personnel from small and medium size manufacturing companies, even though it was open to similar personnel from all size of companies including start-ups. Since the effort targeted the defense manufacturers, not individuals and small number of responses was received, the team could not focus on important aspects like Diversity and Inclusion (DI). However, additional offerings included teaching teachers and students from two low income school districts (urban and rural) 3D scanning.

The author conducted a comprehensive literature review to see if there were similar efforts within academia, by using ASEE’s Peer paper depository system, employing multiple phrases. The phrase “rapid tooling” yielded 4636 entries, “rapid tool making” yielded 4139 entries, “direct rapid tooling” yielded 2910 entries, and finally “indirect rapid tooling” yielded 251 entries. Most of these entries involved one of the keywords within the phrase, yet there were a lot of papers found focusing on rapid prototyping or use of 3D printing in product or system design and development, while some others employed 3D printing as a teaching tool. A very small number of papers actually was centered on rapid tooling like the one by Hoekstra [1], but was not relevant to workforce development. After these initial attempts, a new phrase was selected, “rapid tooling workshop”, yielding 1430 entries, again a large number was not relevant. However, a few papers on the subject in concern were found and some of them actually were based on outreach efforts that was targeting high school students and teachers including multiple papers by Tennessee Tech University [2], [3], [4] but not the industrial workforce. A small number of papers also presented use of subtractive methods (CNC machining) in making patterns including some for thermoforming [5].

The following section of this paper defines the author’s efforts, detailing the structure and content.

Rapid Tooling - A 2-day Workshop

As mentioned earlier, the main target audience for the workshop were the technical personnel from small- and medium-sized manufacturing companies, though it was open to individuals from companies of all sizes, including start-ups. The workshop had a combination of different components: a campus facilities tour, classroom presentations based-on PowerPoint content including definitions/subject fundamentals as well as use cases, demonstrations of software tools, demonstrations of hands-on work, and laboratory exercises.

Author determined the following takeaways as the critical part of this workshop, expecting completed participants having understanding and showing competency in:

- Designing tooling for various manufacturing processes
- Developing ability of rapid tool-making practices, both direct and indirect
- Gaining familiarity with multiple 3D printing and additive manufacturing (AM) technologies, such as Material Extrusion Method (Fused Deposition Modeling (FDM)/Fused Filament Fabrication (FFF)), Binder Jetting, Stereolithography (SLA), and Selective Laser Sintering (SLS)

This section presents the structure and delivery of the workshop as well as the summary of the content presented, as illustrated in the figures below, Figure 1a and b.

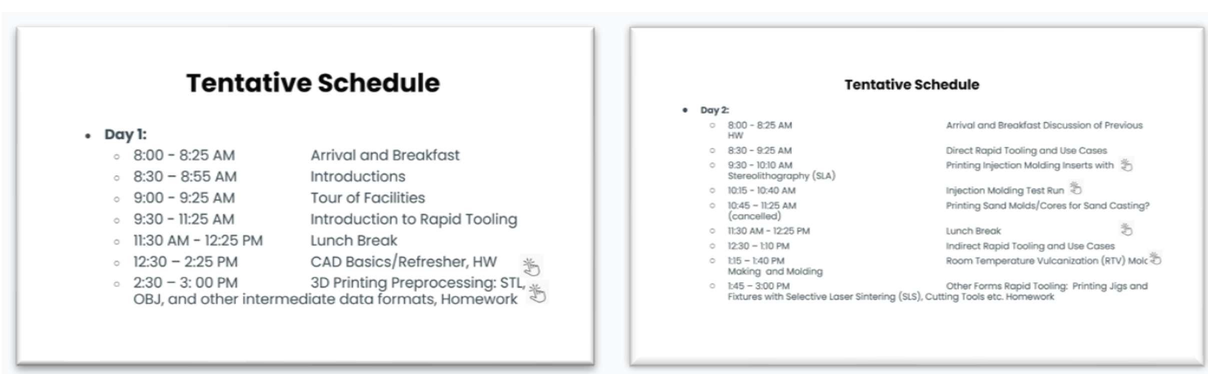


Figure 1. a) Tentative schedule of Day 1 b) Tentative schedule of Day 2 (Homework assignments and Hands-are marked on the schedule)

Introduction to Rapid Tooling

The concept of rapid tooling was defined along with rapid prototyping and rapid (additive) manufacturing. These three were presented as the industrial uses of 3D printing and are given below:

- Rapid prototyping (RP) refers to rapid fabrication of prototypes employing a variety of means: additive, formative, subtractive, and hybrid (a combination of the previous three) means
- Rapid tooling (RT) refers to rapid fabrication of dies/molds, jigs/fixtures, cutters and other tooling components including tooling plates etc.
- Rapid (additive) manufacturing (AM) refers to rapid fabrication of end-use parts and products

Within the initial session, critical points pertaining to rapid tooling were also given to the participants including:

- Rapid tool making lead-times are much shorter than those of tooling made with the conventional methods.
- Rapid tools can be used as prototype or (actual) production tooling.
- Mold/cores made by rapid tooling can be used in a variety of processes such as injection molding or sand casting. Tooling plates made by 3D printing are employed in lost-foam casting, and a similar approach can be taken for printing of porous vents for die-casting.
- CNC cutter inserts and jigs/fixtures can also be a product of rapid tooling efforts.

After a brief introduction to rapid tooling which was presented above, the participants were exposed to the differences between direct and indirect rapid tool making. Direct rapid tool making occurs when the tooling is designed in the CAD environment and 3D printed (Figure 2a), as opposed to indirect rapid tool making where the tool engineers design patterns, 3D print those patterns, and finally manually make the tooling around them (Figure 2b). If a single pattern is employed in making all of the tooling associated with the work, the pattern is referred to as master pattern.

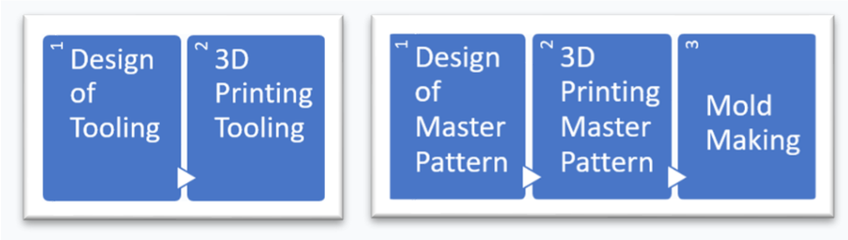


Figure 2. a) Direct rapid tool making workflow b) Indirect rapid tool making workflow

Before a group of use cases could be represented, the workshop participants learned about the developments in processes and materials and their impacts on rapid tooling including a hierarchical chart given in Figure 3, illustrating major segments of rapid tooling practices in indirect and direct rapid tooling as well as soft and hard tooling [6].

The participants also learned that direct rapid tooling can print stronger, harder materials with high temperature endurance when compared to those of indirect rapid tooling. However, direct rapid tooling methods still lack the performance of similar tooling made with conventional manufacturing methods. On the contrary, the direct rapid tooling methods are considered as an economic alternative to the conventional methods, and are suitable for short-run production, such as a few thousand parts. Indirect rapid tooling efforts can produce both soft and hard tooling, and often are associated with prototyping, and not with actual production. It is a good option for testing different materials and processes employing the same master pattern. It can also be used in making a very small number of actual end-use parts. Lead times for making soft molds directly using MEX (Material Extrusion Method – FDM/FFF) and indirectly RTV molding processes may vary slightly, day to a few days. However, lead times for metal indirect tooling are typically longer than direct tooling, with indirect tooling often taking several weeks to months depending on complexity, while direct tooling can be produced in a matter of weeks, however, the exact time frames depend on the specific tooling design, manufacturing process, and the chosen material.

In addition, the author also employed a guide prepared by the Pacific Research Laboratories Engineering, describing pros and cons of the direct and indirect rapid tool making [7].

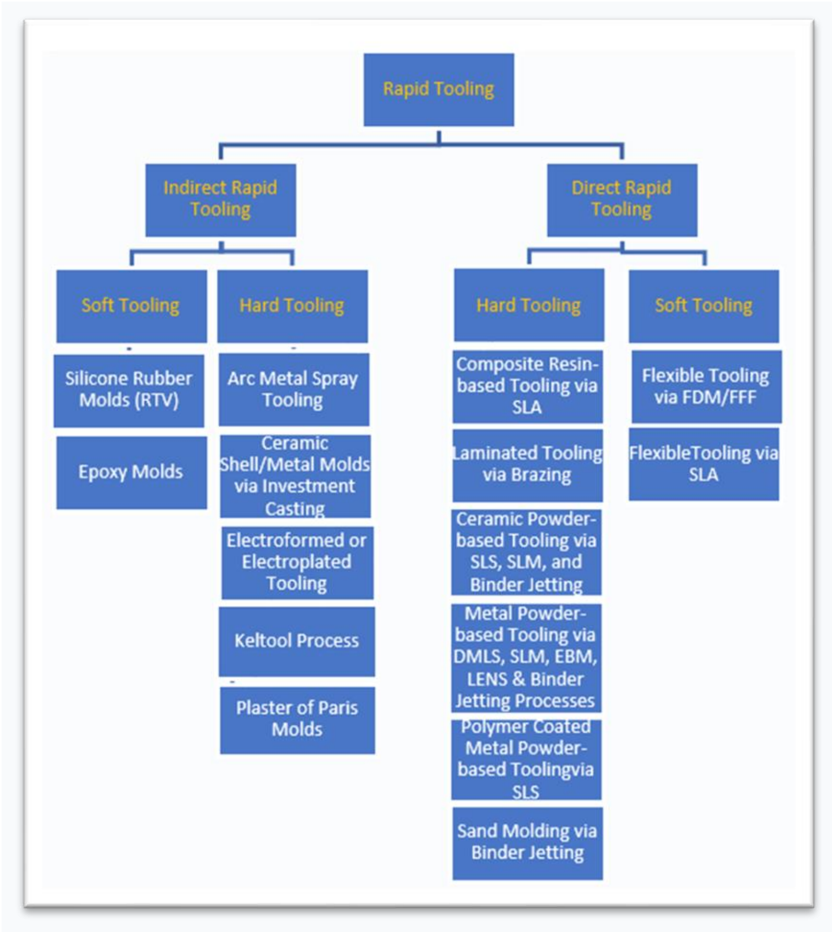


Figure 3. Tool making practices, modified from [6]

Table 1. Pros and cons of direct rapid tool making [7]

Pros	Cons
Faster production and shortened lead times	Often not as robust as prototypes made via indirect rapid tooling
Includes fewer process steps	Mold/tool making without patterns may introduce errors or discrepancies
May require fewer resources	Mold/tool making process needs to be repeated with tool failure
Can produce multiple prototypes from a single mold or tool	May not be appropriate for complex designs or materials
Extremely flexible and productive facilitating making of multiple versions of multiple molds/tooling	Could result in higher development costs due to selection of certain 3D printing technologies and multiple iterations

Table 2. Pros and cons of indirect rapid tool making [7]

Pros	Cons
The master pattern is durable and rarely gets damaged during tool making	Has longer lead times compared to direct rapid tooling
Will likely to invest in one master pattern unless the design changes over time	Involves intermediate process steps that could increase the costs
Can make either hard (for complex designs) or soft tools (for simple and cost-effective designs).	Not always a good option if the design changes significantly during the prototyping (testing and refinement) stage
Less variation amongst multiple copies of certain tools and molds, as they are all based on the same master pattern	May require higher quality materials to make a robust master pattern
Ideal for experimenting with different materials and printing technologies	Not always necessary for simple designs that don't require a high dimension precision or accuracy

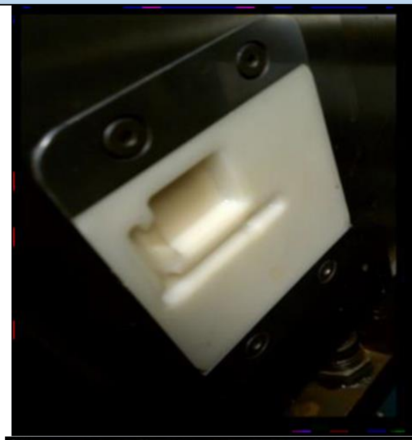
Rapid Tooling Use Cases

During the workshop, multiple use cases were covered in detail. A few of them are presented in the Table 3 below. This gave participants the opportunity to discuss similar issues or requirements they may have in their own work.

CAD Basics/Refresher

Participants were given the choice of completing three basic tutorials (Lessons 1-3 from Getting Started) in SOLIDWORKS training materials, as shown in Figure 4. These tutorials focused on solid modeling, assembly, and technical drawings. The participants were also asked to modify the injection molding insert given below in Figure 5. The insert was for the ejector side of a mold for a BOY injection molding machine (with a clamping force of 220 KN). In addition, the

Table 3. Use cases employed in the workshop

Use case - explanation	Visual
Direct rapid tooling – Case #1: Mold Design and Stereolithography (SLA) Printing of NanoTool Inserts with • Ejector/cover halves • Sprue hole • Runner • Gate • Cavity for the part and a sample of polypropylene (PP) molded parts produced by the insert [8]	 
Direct rapid tooling – Case #2: ExOne is one of the major companies with Binder Jetting technology specifically employed in sand mold printing. • The new S-Max Flex system, incorporates articulated robotics into the Binder-Jetting process with an expanded work volume [9] • A variety of binders are used including Furan (Furfuryl-alcohol based/acid activators), CHP (Ester-cured alkaline phenolic resole binder), HHP (Acid-cured phenolic resole binder), inorganic binders (Water-based alkali-silicate) [10]	 

• ExOne printed green molds and resulting aluminum sand castings	
Indirect rapid tooling [11] – Case #1: • Master Pattern was Binder-Jetted from Stainless Steel (S30) with ExOne's ProMetal R2. • Smooth On's Mold Max 40 (a Tin-cured silicone rubber) was used in making the mold halves. Resin cast was a Polyurethane (Smooth Cast 320).	 
Indirect rapid tooling – Case #2: • ABS master pattern printed with FDM and had to be modified (manually). • Platinum-cured silicone rubber shell mold was made using the pattern. • Resulting part can be seen (with a similar silicone rubber material) [6].	 

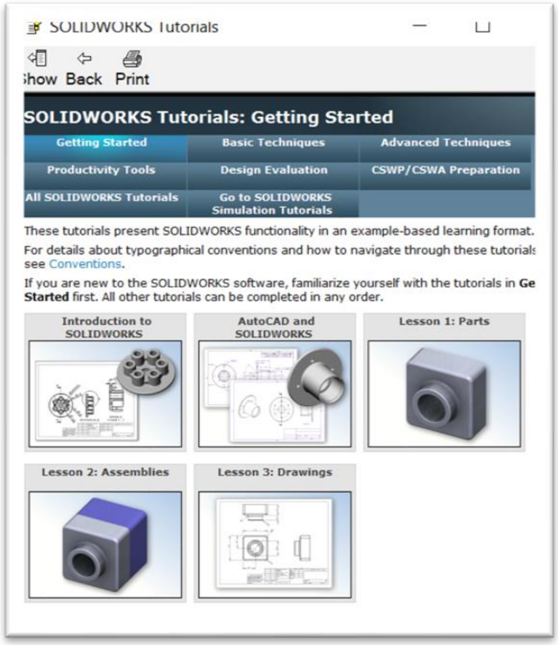


Figure 4. SOLIDWORKS Tutorials

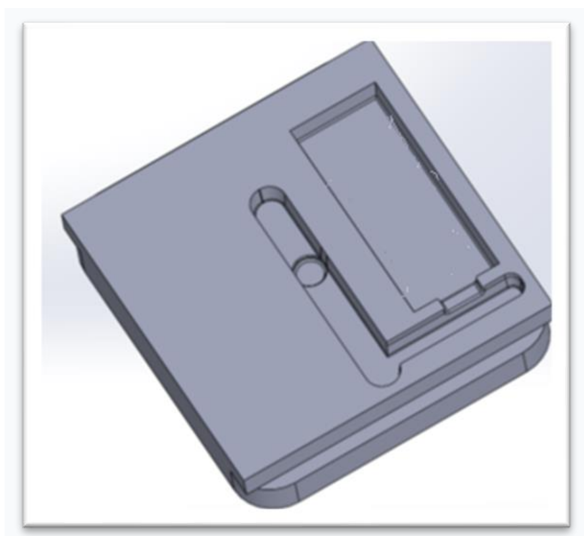


Figure 5. Injection molding insert to be modified (ejector side)

author also encouraged the participants to design their own patterns for the indirect rapid tooling exercises planned within the upcoming activities, especially if they felt good about their CAD skills.

3D Printing Preprocessing: STL, OBJ, and other intermediate data formats

After completion of the CAD activities, the author presented a module on 3D printing pre-processing including the intermediate file formats such as OBJ, PLY, STL, WRL (VRML). These are the outputs of one of the 3D scanners the department has. They are mainly used for

3D printing purposes. Additional formats such as FBX, 3MF, and AMF were also covered. While FBX is designed for and finds use in the digital world such animations, augmented and virtual reality, the other two are becoming common in 3D printing. While 3MF (an XML-based format) supports unit information, color, texture, relative position in space data, AMF has color, texture, material, duplicates, orientation, lattice and meta data. After learning about these intermediate data formats and also direct translators (Figure 6), the participants generated their models in intermediate data formats of STL and 3MF.

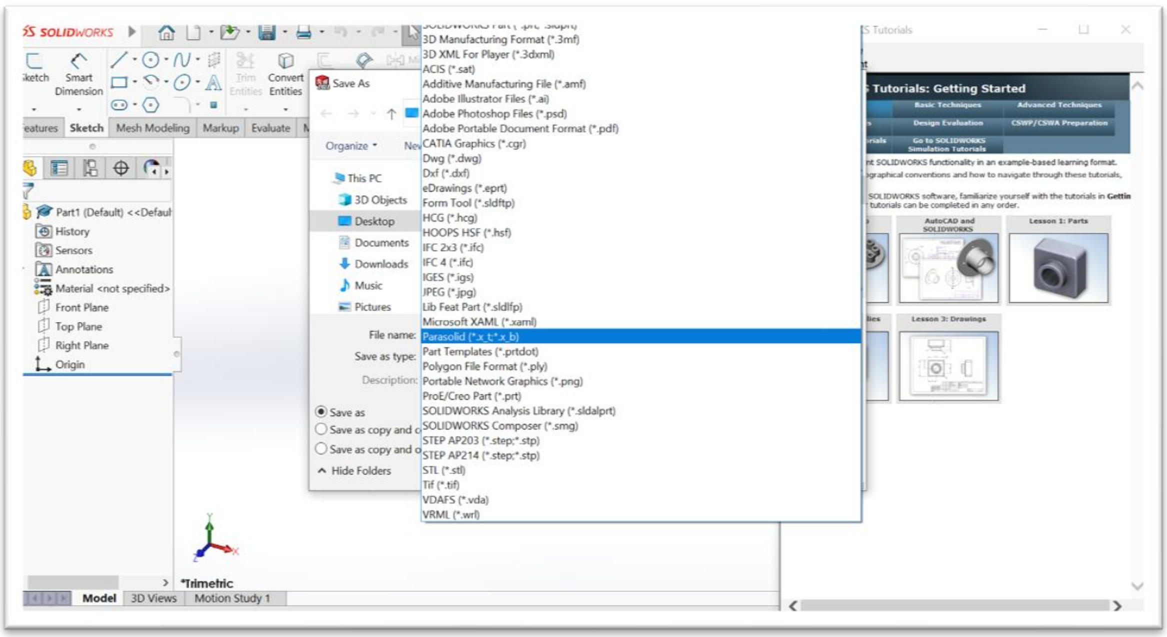


Figure 6. Data formats available in SOLIDWORKS

Hands-on Components

A variety of hands-on activities were originally planned including:

- Printing injection molding inserts with the SLA process and conducting a test run with the Boy (22A) injection molding machine employing those inserts. Two types of Formlabs SLA resins were chosen for this activity due to their high toughness and temperature resistance:
  - Formlabs Rigid 10K, with its data sheet found at [12]
  - Formlabs High Temperature Resin, with its data sheet found at [13]

  An extra activity was added where the participants employed an SLS machine to print their injection molding insert utilizing a glass filled nylon composite material (Nylon 12) [13]. Unfortunately, the injection molding machine broke down during the workshop. Thus, the mold inserts had to be filled under gravity.

Figure 7. SLA and SLS printed mold inserts

- Printing sand molds with an ExOne machine was planned but could not be arranged with our industrial partner. This activity was replaced with the demo of our sand mold printer which is in-progress, as shown in Figure 8 below.

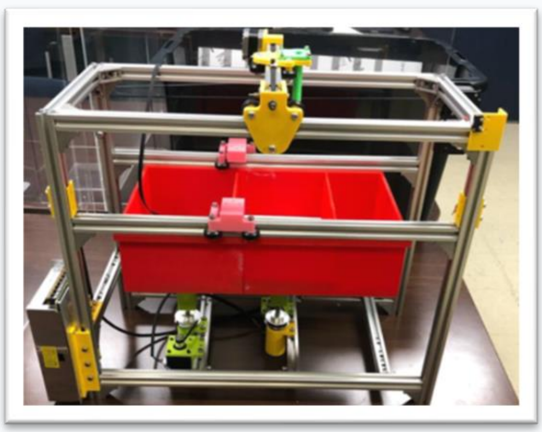


Figure 8. In-house made sand mold printer

- Room Temperature Vulcanization (RTV) silicone rubber mold making and molding activity:

- This activity was employed to demonstrate/accomplish room temperature vulcanization (RTV) mold making and subsequent molding. Materials chosen are Mold Max 40 (a Shore-A 40 tin cured silicone rubber) for making the (positive) mold and EpoxAcast 655+ HT (an aluminum filled castable epoxy resin with its high temperature hardener) for making the mold's composite negative, the actual mold insert. Figures 9 a, b, c, and d depict the process and its outcome. Figure 10 a, b is the activity for making another negative copy of the tooling, this time with RTV molding, or basically indirect rapid tooling.

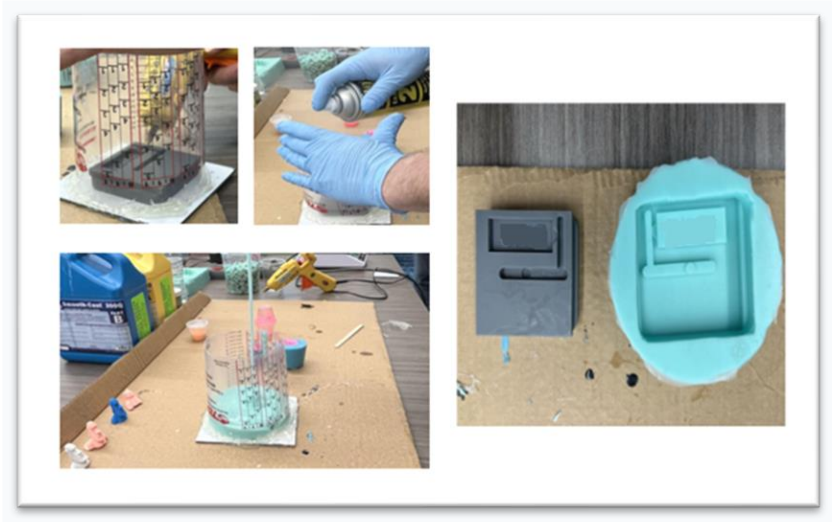


Figure 9. a) Preparation of the mold by introducing a cover to the SLA printed mold insert b) Application of a mold release agent c) Application of the silicone rubber mold mix (with parts A and B) d. Initial (grey) negative and resulting (green) positive tooling.

Figure 10. a) Weighing the resin b) Pouring the resin into the silicone rubber mold to obtain another negative, this time using indirect rapid tooling and a metal filled EpoxAcast 655 material (grey).

- Similar process was repeated by the participants after they used MEM (FDM/FFF) printers to print a pattern (Figure 11a), then build a silicone rubber mold around their patterns. Clear resin (Smooth Cast 325) with pigmentation was used to obtain the light-colored parts also shown in Figure 11a.

Figure 11. a) FDM/FFF printed pattern (dark blue), molded pieces (light-pink and -blue) b, c, d) Pouring the resin into silicone rubber mold

- Other Forms Rapid Tooling: Printing Jigs and Fixtures with SLS. Material selected for this activity is the same as the injection molding material presented above [14]. Figure 12 depicts the Nylon 12 GF (a glass-filled Nylon) fixture base (grid) plate and locator pins during the development of the activity, along with high strength (white) clamping components: including clamps (two different types) and t-slots and metal bolts. White parts were later replaced with SLS printed Nylon 12 GF.

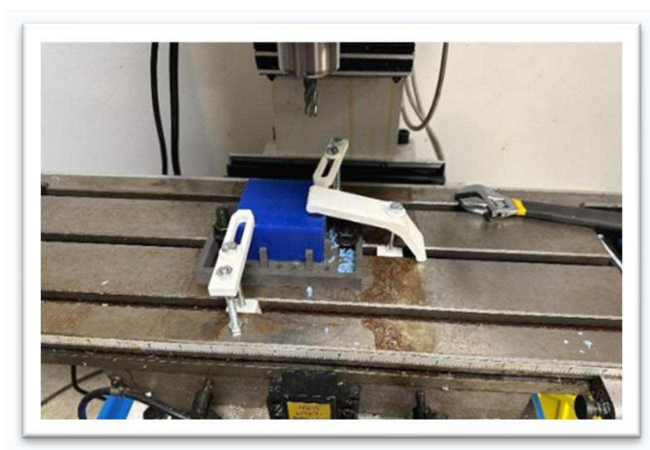


Figure 12. A 3D printed fixture – a combination of SLS (gray) and MEM (FDM/FFF) (white) parts

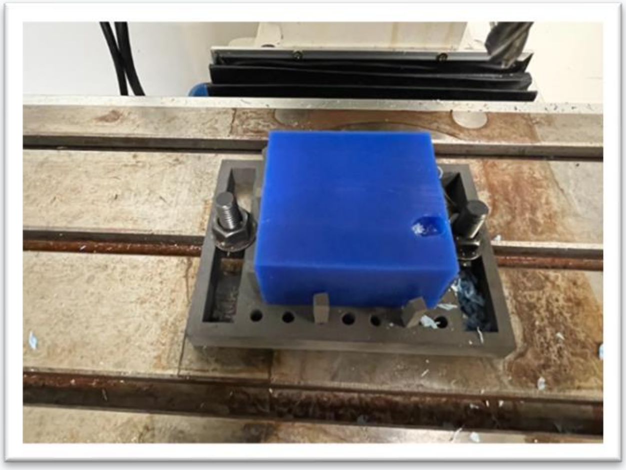


Figure 13. Machining marks after removal of the clamps

Figure 13 shows the set-up after the clamps were removed. This figure allows a better look to the baseplate and locator pins. Figure 14 shows the complete set of pieces for this activity after replacing the clamps made by MEM (FDM/FFF) with the SLS ones.

Figure 14. Completed machining fixture -printed mainly by SLS by the participants.

Efforts of Integrating the Workshop Content into an Undergraduate Course

These workforce development efforts also lead to changes in the author's undergraduate curriculum where 3D printing content lies. Some of the workshop helpers took the author's class and they were already well-versed in the components developed during this workshop. Components like SLS printing, jig and fixture design was translated to the undergraduate course along with the negative and positive tool making with indirect rapid tooling, enriching the course content and making it more hands-on.

If we study this effort, in the eye of an ABET evaluator, we can easily say that the following student outcomes were targeted, even though this was such short event. Yet, the participants completed their obligations for the workshops indicating high competencies in the requirements relevant to SO1 and SO2. They also did additional studies to address a few homework assignments (SO7).

- SO1 - an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics. Students worked with a variety of materials, and were exposed to a variety of chemical reactions (including exothermic) and their outcome, as they made hard/soft molds and consequently made hard /soft parts within those molds, preparing themselves for future
- SO2 - an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors. Students were exposed to a variety of 3D printing and AM processes along with their uses in short- and long-run (volume) tool making and their importance including manufacturing economics.
- SO7 - an ability to acquire and apply new knowledge as needed, using appropriate learning strategies. Students were given a technological boost to their arsenals, which can easily be translated to other engineering projects.

Conclusions and Future Work

The effort was successful in a way, accomplishing most of the planned activities and giving hands-on opportunity to the participants. However, it had small number of engineers from the industry, only 2 registering. Thus, the organizers allowed a materials science Ph.D. student from a nearby research university to participate. They also had 5 undergraduate students from their schools participating. In terms of the accessibility issues regarding the sand mold printing and injection molding, they are being handled. A new injection molder was purchased by the department, and communications with the partner on sand mold printing has been positive.

The author determines the three key-takeaways for the participants including:

- Designing tooling for various manufacturing processes
- Developing ability of rapid tool-making practices, both direct and indirect
- Gaining familiarity with multiple 3D printing and additive manufacturing (AM) technologies, such as Fused Deposition Modeling (FDM)/Fused Filament Fabrication (FFF), Binder Jetting, Stereolithography (SLA), and Selective Laser Sintering (SLS)

All of these take-aways was successfully realized and the participants successfully completed their tasks to gain these critical skills and information, designing and making their own tooling, and successfully operating these machines, doing their post-processing operations.

References

[1] N. L. Hoekstra, "Tool design and concurrent engineering through six rapid tooling construction methods using rapid prototype models," presented at the 2000 Annu. Conf., St. Louis, MO, Jun. 2000. doi: 10.18260/1-2--8778.

[2] A. McGough, C. Nocton, K. Patton, and I. Fidan, "Hands on workshop-based learning of rapid prototyping," presented at the 2004 Annu. Conf., Salt Lake City, UT, Jun. 2004. doi: 10.18260/1-2--13726.

[3] I. Fidan, O. Elkeelany, L. Goolsby, S. Serkownek, and T. Dean, "Broadening rapid prototyping awareness via P16 stem teacher workshops," presented at the 2008 Annu. Conf. & Expo., Pittsburgh, PA, Jun. 2008. doi: 10.18260/1-2—3581.

[4] I. Fidan and K. Patton, "Work in progress: Rapid prototyping instructional and hands-on delivery for K16," in *Proc. Front. Educ. 36th Annu. Conf.*, San Diego, CA, Oct. 2006, pp. S3G-7–S3G-8. doi: 10.1109/FIE.2006.32267.

[5] L. Reifschneider, "Rapid prototype tooling to teach net shaped manufacturing," presented at the 2009 Annu. Conf. & Expo., Austin, TX, Jun. 2009. doi: 10.18260/1-2--5686.

[6] A. Sirinterlikci and Y. Ertekin, "Applications of 3D Printing," in *A Comprehensive Approach to Digital Manufacturing*, A. Sirinterlikci, Ed. Cham, Switzerland: Springer, 2023, pp. 117–134. doi: 10.1007/978-3-031-25354-6_7.

[7] "Two Types of Rapid Tooling for Prototyping," Design Blog, Pacific Research Labs, [Online]. Available: https://www.pacific-research.com/two-types-of-rapid-tooling-for-prototyping-prl/. Accessed: Sep. 20, 2022.

[8] A. Sirinterlikci, Z. Czajkiewicz, J. Doswell, and N. Behanna, "Direct and indirect rapid tooling," in *2009 Rapid/3D Scanning Conf.*, Chicago, IL, 2009.

[9] "ExOne S-Max Review, an Industrial 3D Printer (Binder Jetting)–Aniwaa," Aniwaa, [Online]. Available: https://www.google.com/search?q=https://www.aniwa.com/product/. Accessed: Sep. 20, 2022.

[10] "3D Materials & Binders–ExOne," ExOne, [Online]. Available: https://www.google.com/search?q=https://www.exone.com/en-US/sand-casting. Accessed: Sep. 20, 2022.

[11] A. Sirinterlikci, O. Uslu, N. Behanna, and M. Tiryakioglu, "Preserving historical artifacts through digitization and indirect rapid tooling," *Int. J. Mod. Eng.*, vol. 10, no. 2, pp. 42–48, 2010.

[12] "Formlabs Rigid 10K Resin," Formlabs, [Online]. Available: https://formlabs-media.formlabs.com/datasheets/2001479-TDS-ENUS-0.pdf. Accessed: Sep. 20, 2022.

[13] "Formlabs High Temperature Resin," Formlabs, [Online]. Available: https://formlabs-media.formlabs.com/datasheets/High_Temp_Technical.pdf. Accessed: Sep. 20, 2022.

[14] "Formlabs Nylon 12GF Powder," Formlabs, [Online]. Available: https://formlabs.com/eu/blog/introducing-nylon-12-gf-powder/. Accessed: Sep. 20, 2022.