Integration of Metal Additive Manufacturing Using Fused Deposition Modeling in Mechanical Engineering Education

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Abstract

This paper presents the integration of additive manufacturing techniques using metal-polymer and fiber-polymer filaments in mechanical engineering education. Currently, students need to outsource the production of high-performance plastics and stainless-steel parts for their senior capstone project to third-party vendors which require long lead times and cost more than the methods presented in this paper. Considering the ease of use and capabilities of additive manufacturing techniques like fused deposition modeling (FDM) 3D printing, students can greatly benefit from using these techniques for their senior capstone projects. The content of the paper explores and proposes the use of metal-polymer and fiber-polymer filaments using FDM printers as a part fabrication resource for senior capstone projects for mechanical engineering students. The use of additive manufacturing provides students with much-needed industry skills like prototyping, tolerancing, and design experience while metal-polymer and fiber-polymer filaments provide better, enhanced properties to printed models and open up new horizons for 3D printing functional parts. Integrating these novel materials into engineering education can help students be successful in the ever-changing engineering field.

Keywords

Undergraduate Student Paper, Mechanical Engineering, Metal Additive Manufacturing, Fused Deposition Modeling, Design for Manufacturing

Nomenclature

FDM – Fused Filament Deposition

DFM – Design for Manufacturing

PLA – Polylactic Acid

PVA – Polyvinyl Alcohol

PETG – Polyethylene Terephthalate Glycol

ABS – Acrylonitrile Butadiene

PC - Polycarbonate

PA – Polyamide (Nylon)

TVF – The Virtual Foundry^{TM}

MH – MatterHackers^{TM}

SS – Stainless Steel

CF – Carbon Fibre

GF – Glass Fibre

Hotend – the part of the 3D printer that melts and extrudes the filament.

Introduction

The senior capstone project for mechanical engineering students at the University of Arkansas spans two semesters. The first segment of this project requires students to select an engineering problem and learn and apply the design process along with project management skills to deliver a solution as a team within a specified budget and timeline. The second segment involves implementing this solution and testing its performance [1].

With the easy accessibility of FDM 3D printing, students can use additive manufacturing using readily available materials such as PLA, PETG, and ABS. Materials such as PA, PC, and fiber-polymer filaments like PA-GF and PA-CF let students experiment with unique print parameters, and enhanced physical, and thermal properties. Introducing metal-polymer filaments can further help students in manufacturing metal parts using 3D printing. Utilizing 3D printing for metal parts with complex geometries can greatly reduce costs compared to outsourcing the fabrication of stainless-steel parts to third-party vendors. Combining these materials and processes helps students not only gain manufacturing experience but these materials also provide important insights into the material properties and design considerations.

Design for manufacturing (DFM) is a crucial part of engineering, and metal-polymer and fiber-polymer filaments provide new opportunities and experiences to engineering students. This also promotes research in the field of additive manufacturing by inspiring students to look for new manufacturing methods for metal and fiber-polymer fabrication. Training students and allowing them to use such filaments also allows them to have a better understanding of the various materials available for 3D printing and create better parts for their capstone projects. A preparatory workshop program to train students on how to use 3D printing for metal and fiber-polymer parts can also help in providing a new, time and cost-efficient resource. This will also result in a better capstone project experience and better learning outcomes for the students involved.

Objectives

The objectives of this training program are to provide a dedicated resource for students to use for their senior capstone project and to help students understand the different materials that could be used in 3D printing. This training will be optional if students choose to not use 3D-printed metal or fiber-polymer parts. The program will be introduced as a preparatory workshop for capstone students which will allow the students to safely and successfully 3D print reliable metal and fiber-polymer parts. It will complement pre-existing resources for students to use for their senior capstone projects. It will also include topics like material types and their applications, sintering processes, common print parameters for materials, and the difference between printer types.

ASME's Vision 2030 report, which began in 2008, analyzed the perspectives of over 1,400 engineering managers in industry, and mechanical engineering education leaders from 80 universities to set objectives for standards for students. These standards stated, "to provide richer and more extensive practice-based engineering experience for students", "increase familiarity with how devices are made and work", and "increase applied engineering design-build-test experiences throughout the degree program." The diversity and inclusion objectives stated, "expand the kinds of problems that we are asking students to address" and "engage students throughout their degree program with active discovery-based learning" [3], [4].

All the above-stated objectives will be fulfilled by this training program by providing an extensive practice-based engineering experience and increasing applied engineering design-build-test experiences while also including thorough knowledge of errors and practices to fix the errors.

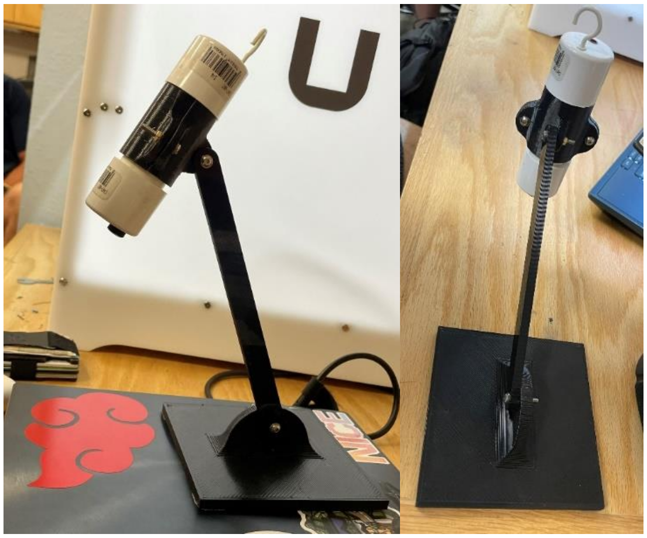


Figure 1 – *A 3D-printed holder for a filament heater. This holder was printed using Ultimaker PLA. 3D printing can be used for many such applications for functional parts [6].*

Resources

These preparatory workshop sessions will require 3D modeling software like Dassault Systèmes SolidWorks or Autodesk's Fusion 360, an FDM 3D printer, slicing software for the 3D printer, a kiln, and a ventilation setup.

The 3D printers must have the ability to print abrasive materials such as PA-CF, PA-GF, SS-polymer, etc. which requires a full metal hotend with hardened steel nozzles. The printer must also be enclosed with a heated bed to be able to print PA and PC-based filaments. Open-source printers would be preferred as they are comparatively affordable and easier to maintain in the long run. Nylon-based filaments also require to be stored in dry environments, so having a filament dryer is a must (**Table 1**). The slicer software will be dependent on the printer that is being used.

Requirements	Reasons
Open Source	Easy serviceability, Easy to find spare parts, Free slicers
Full Metal Hotend	A full metal hotend lets a printer use high-temperature filaments like PC and PA. Regular hotends have PTFE lining which starts degrading at temperatures above 260°C which releases noxious fumes.
Hardened Steel Nozzle	A hardened steel nozzle is required to use abrasive filaments like NylonX (PA-CF), NylonG (PA-GF), and SS-polymer. A regular brass or SS nozzle would get internally scratched by these filaments and get damaged resulting in failed prints.
Enclosure	High-temperature filaments like PC, ABS, and PA-based filaments require a heated environment to print which is provided by an enclosure to keep the heat from the build plate inside the printer.
Filament Dryer	Nylon-based filaments readily absorb moisture due to which they need to be stored in a dry environment. They need to be dried frequently to print properly.

Table 1 *–Requirements for a 3D printer to be a good resource for students to use on their senior capstone project [6], [12], [13].*

98% Nitric acid and kiln firing will be used for debinding and sintering the BASF SS-polymer parts [20]. This will require faculty supervision and proper ventilation. Along with these, the process will also require heat-resistant gloves, aprons, and other heat-resistant equipment. There must be demonstrations for using the kilns for every student and strict operating procedures should be set to ensure the safety of the users. The nitric acid catalytic debinding should initially be done by faculty or TAs who can do it safely with appropriate equipment. Students can then be trained to use 98% nitric acid for catalytic debinding. Those who complete this training can be provided a faculty-signed document certifying them for safe usage of 98% nitric acid for catalytic debinding (**Figure 2, Figure 3**) of SS-polymer parts [9]. The Virtual Foundry filaments can be debound and sintered using a kiln, sintering carbon, and TVF’s steel blend (**Figure 4**) [8].

Figure 2 – *Printing, debinding, and sintering process chart for BASF Forward AM 17-4 PH SS filament [9].*

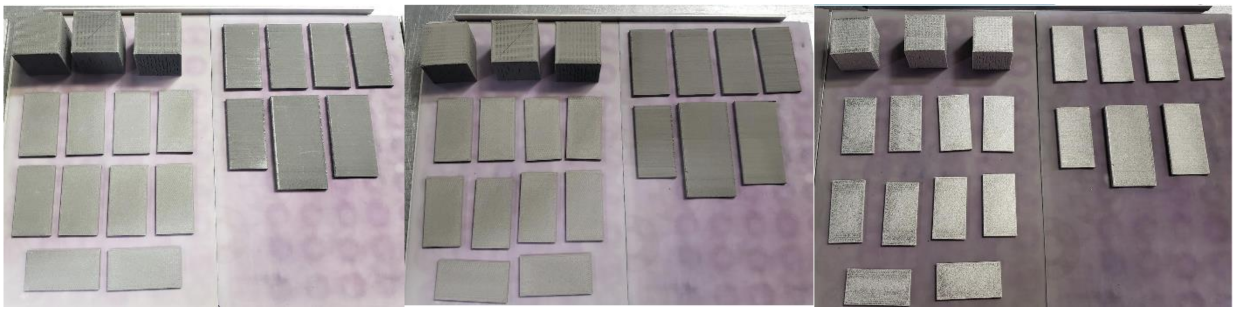


Figure 3 – *Printed (left), debound (middle), and sintered (right) parts. The printed parts were sent to MatterHackers using BASF Forward AM Ultrafuse 17-4 PH Processing Ticket and MatterHackers provided the debinding and sintering services. Images provided by MatterHackers [9].*

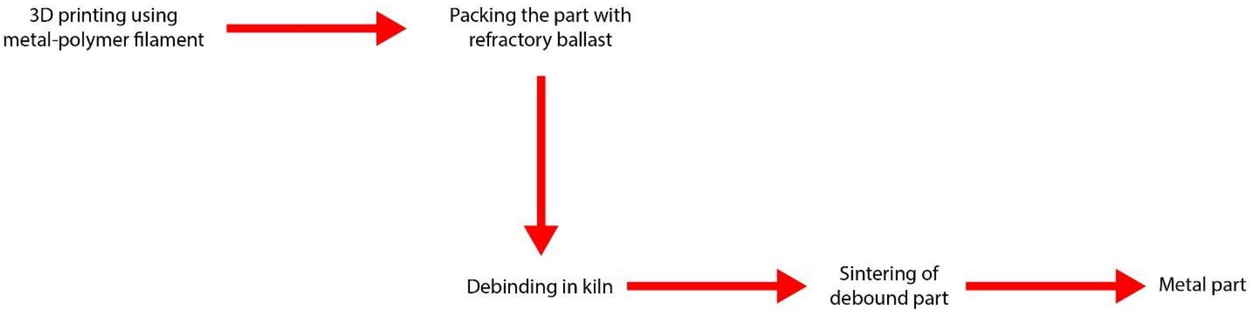


Figure 4 – *Printing, debinding, and sintering process chart for The Virtual Foundry filaments[7].*

An alternative for sintering the SS-polymer parts is to use the services provided by MatterHackers^{TM}. They require the printed SS-polymer parts to be shipped in 1kg batches and take around 2 weeks to sinter and ship them back (**Figure 3, Figure 5**). This requires the parts to be perfectly printed and processed after printing. Post-print processing includes removing any stray filament on the part and sanding the print to smoothen out the layer lines (optional, only needed for smooth surfaces post-sintering). This method costs $50 -$80 and prints 1kg of parts. If a 1kg spool of BASF Forward AM Ultrafuse 17-4 PH SS filament is purchased for $129.00, it comes with an included processing ticket. This is recommended for safety, cost, and time-saving measures [9].

Printed SS-polymer parts

Sintered SS parts

Figure 5 – *Functional parts printed using BASF Forward AM 17-4 PH Stainless Steel Filament and sintered through MatterHackers' Processing Ticket for 17-4 PH SS Filament [7], [9].*

Methods

This preparatory workshop will start with basic knowledge about 3D printing that will be followed by a thorough understanding of the parts of a 3D printer and 3D printing with common materials like PLA (**Figure 1**) and ABS. Next, the students will be introduced to advanced filaments like PC, PA-CF, PA-GF, and SS-polymer.

Students will be informed about the nozzle types, sizes, and applications (**Table 2**). They will also be given information about build plate types and their uses. Subsequently, students will learn about techniques like orientation of models for printing metal parts, e.g., large cavities must be supported, proper infill percentages, etc. They will be introduced to the sintering process, and later trained, which will help them in understanding the shrinkage factors, supporting the prints during sintering, and other important sintering procedures. Once students complete these trainings, they can be granted authorization by the department that certifies their ability to use these resources without supervision.

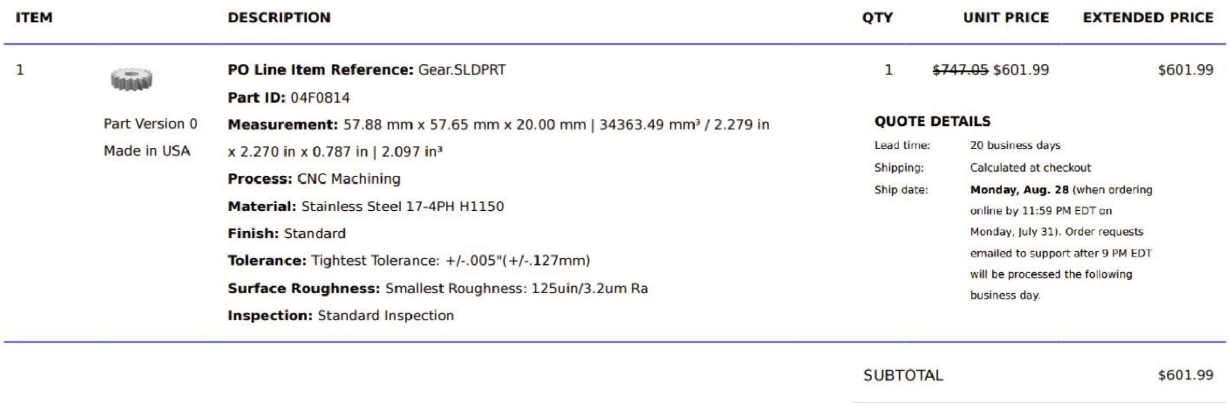
Given this information, students should be able to freely print fiber-polymer and metal filaments using the FDM printers.

Nozzle Material	Maximum Nozzle Temperature	Use	Properties
E3D Brass	~300°C	For common polymers like PLA, ABS, PETG, Nylon	Very prone to scratches, cannot use abrasive materials
E3D Stainless Steel	~ 500°C	For lightly abrasive materials, Food grade materials	Harder than brass, cannot use metal-polymer or ceramic-polymer materials
E3D Hardened Steel	~ 500°C	For all materials, including highly abrasive metal-polymer and ceramic-polymer materials	Very hard, scratch-resistant when using any material
Olsson Ruby	> 500°C	For all materials, including highly abrasive metal-polymer and ceramic-polymer materials	Tips are made with ruby, and will not get scratched. Can be used for very high-temperature materials.

Table 2 – *Properties of different nozzles and their uses. The nozzles may differ from manufacturer to manufacturer due to which the names are added.* [10], [11]

Applications

Engineering problems require a multitude of factors to be considered, and the parts designed require specific geometries, materials, and thermal properties. For senior capstone design projects, students usually have to outsource many parts to third-party vendors which leads to high costs and long lead times. Using metal-polymer and fiber-polymer 3D printing as a resource lets students print and post-process their parts in-house, leading to lower costs, faster part production, and rapid prototyping. This cost and time reduction also leads to better final products as rapid prototyping lets students experiment with multiple iterations while consuming less time compared to third-party services.



ITEM		DESCRIPTION	QTY	UNIT PRICE	EXTENDED PRICE
1	Part Version 0 Made in USA	**PO Line Item Reference:** Gear.SLDPRT **Part ID:** 04F0814 **Measurement:** 57.88 mm x 57.65 mm x 20.00 mm | 34363.49 mm³ / 2.279 in x 2.270 in x 0.787 in | 2.097 in³ **Process:** CNC Machining **Material:** Stainless Steel 17-4PH H1150 **Finish:** Standard **Tolerance:** Tightest Tolerance: +/-.005"(+/-.127mm) **Surface Roughness:** Smallest Roughness: 125uin/3.2um Ra **Inspection:** Standard Inspection	1	~~$747.05~~ $601.99	$601.99

QUOTE DETAILS

Lead time:	20 business days
Shipping:	Calculated at checkout
Ship date:	**Monday, Aug. 28** (when ordering online by 11:59 PM EDT on Monday, July 31). Order requests emailed to support after 9 PM EDT will be processed the following business day.

SUBTOTAL $601.99

Figure 6 – *Quote from www.xometry.com for a gear to be CNC machined in 17-4 PH SS. This gear will cost $601.99 to be machined and will have a lead time of 20 business days [21].*

For a gear to be machined in 17-4 PH SS, a 3rd party manufacturer [21] charges $601.99 (**Figure 6**). The same gear printed with 100% infill density weighs 226g (**Figure 7**), and costs $40.55, considering the filament cost to be $129.00/kg and the processing ticket cost to be $50 [9], [20]. This makes the 3D-printed gear approximately 14.8 times cheaper compared to getting it fabricated by a third-party vendor[21].

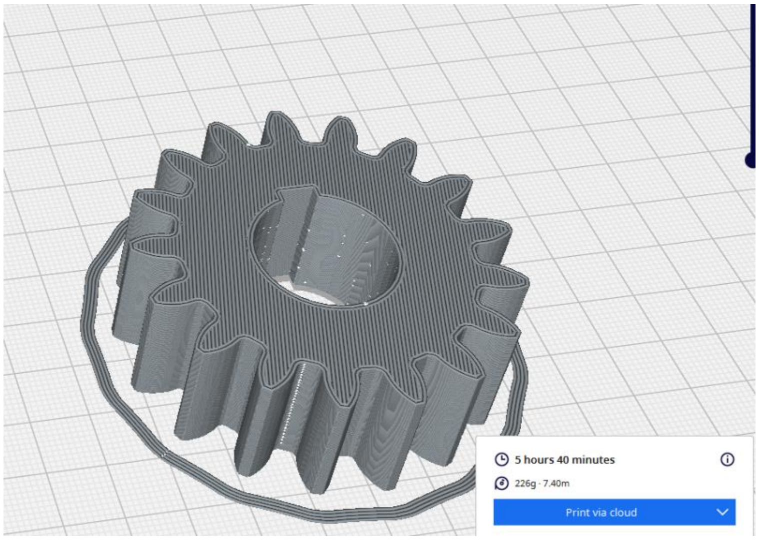


Figure 7 – *Gear being printed with BASF Forward AM 17-4 PH Stainless Steel Filament; the print will weigh 226g and use 7.40m of the filament (bottom left) [14]. Image from Ultimaker Cura.*

Parts that require high thermal resistance (approx. 150°C) can be printed in Nylon and Polycarbonate filaments. Filaments like PC also come mixed with other materials like ABS to make filaments that have flame retardant and self-extinguishing properties. Filaments such as MH NylonX (PA-CF) and MH NylonG (PA-GF) come with carbon fiber and glass fiber mixed in PA12 Nylon. These additives reinforce the nylon polymer and add rigidity to the parts. NylonX and NylonG can be used at temperatures up to 160°C due to their high heat deflection temperatures and maximum usage temperatures (**Figure 8**) [13]. A table of different materials, their extruding temperatures, properties, and requirements is provided ahead (**Table 3**).

Material	Nozzle Temperature	Properties	Special Requirements
PLA	200°C - 210°C	Low heat resistance, stiff	Optional - Build Plate Temperature: 40°C
PETG	225°C - 245°C	More durable than PLA, higher heat resistance compared to PLA	Build Plate Temperature: ~85°C
PVA	215°C - 225°C	Mainly used as water-dissolvable support	Very dry storage environment
ABS	225°C - 260°C	Stronger and more heat resistant than PLA	Enclosed Printer, Build Plate Temperature: 80°C - 90°C
PA (Nylon)	230°C - 260°C	More durable and heat resistant than PLA, PETG, and ABS	Enclosed Printer, Build Plate Temperature: 40°C - 60°C
PC	260°C - 280°C	More heat resistant, stiffer, and stronger than ABS, PLA, Nylon	Enclosed Printer, Build Plate Temperature: 110°C
MH NylonX (PA-CF)	250°C - 265°C	More rigid than Nylon, has better durability than all the above materials	Enclosed Printer, Build Plate Temperature: 60°C - 80°C, Bed Adhesive
MH NylonG (PA-GF)	250°C - 265°C	More rigid than Nylon, has better durability than all the above materials	Enclosed Printer, Build Plate Temperature: 60°C - 80°C, Bed Adhesive
BASF Ultrafuse 17-4 PH (SS-polymer)	230°C - 250°C	Turns into a stainless-steel part once sintered	Build Plate Temperature: 90°C - 120°C, Bed Adhesive, Catalytic Debinding
TVF 17-4 PH (SS-polymer)	205°C - 235°C	Turns into a stainless-steel part once sintered	Build Plate Temperature: 40°C - 50°C, Bed Adhesive, Heat Debinding

Table 3 – *Properties of different filaments and special requirements. The filaments' temperatures and properties may differ from manufacturer to manufacturer due to which the names are added [6] – [9], [12], [13], [15].*

Figure 8 – *Functional parts for high-temperature applications (140°C - 150°C) printed in NylonG PA-GF (left) and NylonX PA-CF (right) [12], [13], [15].*

For parts that need to be long-lasting, hard, and have good wear resistance, stainless steel is a preferred choice. Stainless steel resists corrosion and is mechanically durable leading to its use to make parts like gears, springs, etc. (**Figure 9, Figure 10**) Parts that will be under load and constant wear are common in a capstone project, and stainless steel is expensive to procure, requires long lead times from third party manufacturers, and is difficult to machine. 3D printing parts with stainless steel filaments greatly reduces the cost and time taken to fabricate a metal part [17].

Figure 9 – *Gear printed with BASF Forward AM 17-4 PH Stainless Steel Filament (left). Gear in stainless steel after sintering (middle). The gear inside the assembly is fully made using BASF's SS Filament (right). [7], [9], [18]. Image from www.matterhackers.com*

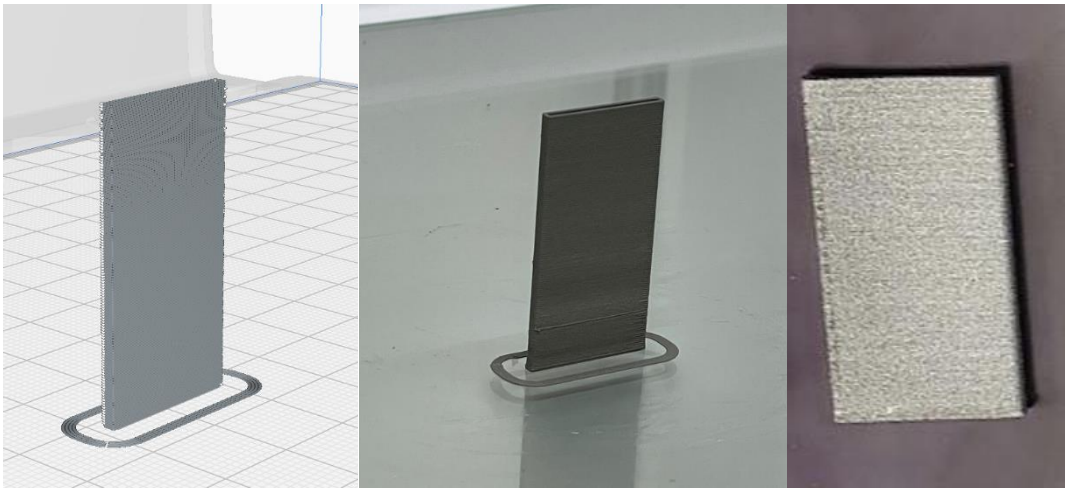
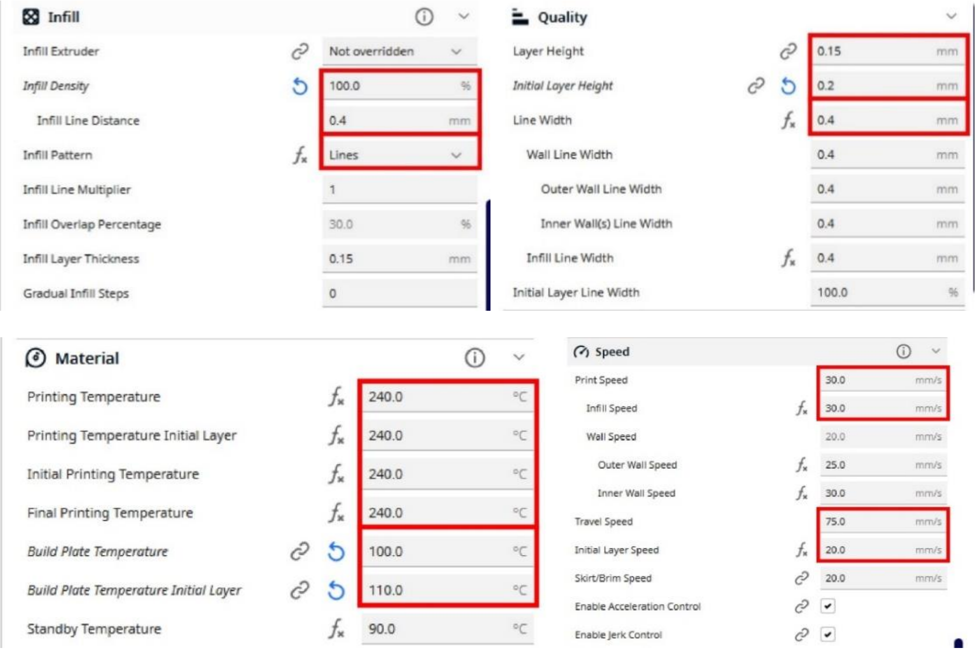


Figure 10 – *The object being printed with BASF Forward AM 17-4 PH Stainless Steel Filament using an Ultimaker S5 3D printer. Object in slicer (left), printed object (middle), and sintered SS object (right). The object was sintered through MatterHackers using the processing ticket [9], [14], [18].*



Infill

Setting	Value
Infill Extruder	Not overridden
Infill Density	100.0 %
Infill Line Distance	0.4 mm
Infill Pattern	Lines
Infill Line Multiplier	1
Infill Overlap Percentage	30.0 %
Infill Layer Thickness	0.15 mm
Gradual Infill Steps	0

Quality

Setting	Value
Layer Height	0.15 mm
Initial Layer Height	0.2 mm
Line Width	0.4 mm
Wall Line Width	0.4 mm
Outer Wall Line Width	0.4 mm
Inner Wall(s) Line Width	0.4 mm
Infill Line Width	0.4 mm
Initial Layer Line Width	100.0 %

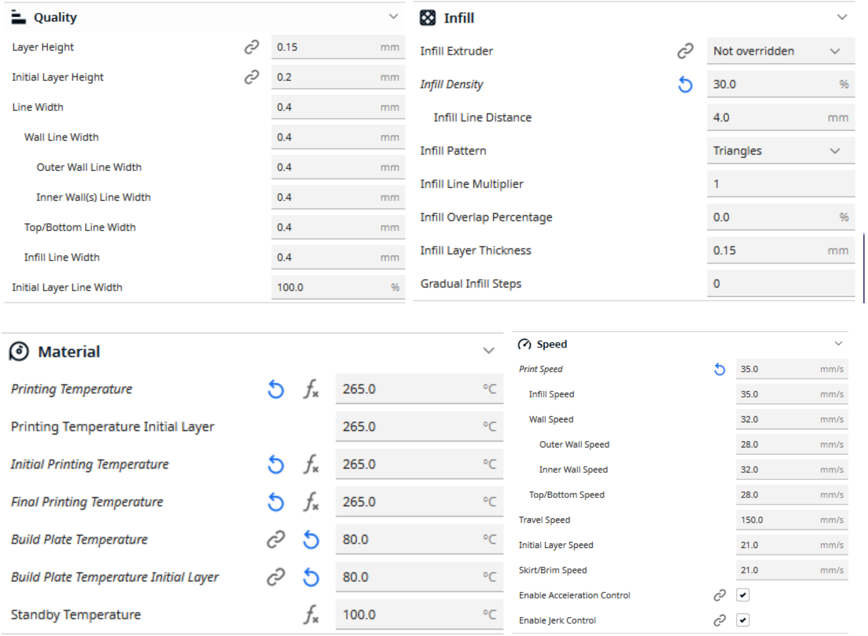
Material

Setting	Value
Printing Temperature	240.0 °C
Printing Temperature Initial Layer	240.0 °C
Initial Printing Temperature	240.0 °C
Final Printing Temperature	240.0 °C
Build Plate Temperature	100.0 °C
Build Plate Temperature Initial Layer	110.0 °C
Standby Temperature	90.0 °C

Speed

Setting	Value
Print Speed	30.0 mm/s
Infill Speed	30.0 mm/s
Wall Speed	20.0 mm/s
Outer Wall Speed	25.0 mm/s
Inner Wall Speed	30.0 mm/s
Travel Speed	75.0 mm/s
Initial Layer Speed	20.0 mm/s
Skirt/Brim Speed	20.0 mm/s
Enable Acceleration Control	☑
Enable Jerk Control	☑

Figure 11 – *Print settings for* **Figure 10** *in Ultimaker Cura 5.3.0. Settings outlined in red are the most crucial printing parameters [14].*



Quality

Layer Height	0.15 mm
Initial Layer Height	0.2 mm
Line Width	0.4 mm
Wall Line Width	0.4 mm
Outer Wall Line Width	0.4 mm
Inner Wall(s) Line Width	0.4 mm
Top/Bottom Line Width	0.4 mm
Infill Line Width	0.4 mm
Initial Layer Line Width	100.0 %

Infill

Infill Extruder	Not overridden
Infill Density	30.0 %
Infill Line Distance	4.0 mm
Infill Pattern	Triangles
Infill Line Multiplier	1
Infill Overlap Percentage	0.0 %
Infill Layer Thickness	0.15 mm
Gradual Infill Steps	0

Material

Printing Temperature	265.0 °C
Printing Temperature Initial Layer	265.0 °C
Initial Printing Temperature	265.0 °C
Final Printing Temperature	265.0 °C
Build Plate Temperature	80.0 °C
Build Plate Temperature Initial Layer	80.0 °C
Standby Temperature	100.0 °C

Speed

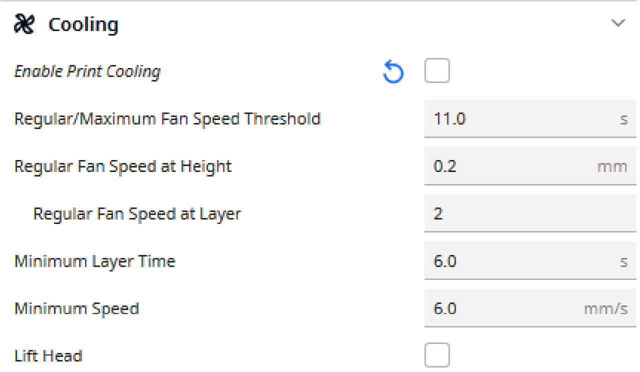
Print Speed	35.0 mm/s
Infill Speed	35.0 mm/s
Wall Speed	32.0 mm/s
Outer Wall Speed	28.0 mm/s
Inner Wall Speed	32.0 mm/s
Top/Bottom Speed	28.0 mm/s
Travel Speed	150.0 mm/s
Initial Layer Speed	21.0 mm/s
Skirt/Brim Speed	21.0 mm/s
Enable Acceleration Control	☑
Enable Jerk Control	☑

Figure 12 – *Print settings for* **Figure 8** *in Ultimaker Cura 5.3.0. Settings outlined in red are the most crucial printing parameters [14].*

Printing parameters are among the most important aspects of printing metal and fiber-polymer filaments because these materials require completely different print settings. Infill is the lattice structure inside the printed object. Infill density must be 100% for the metal part (**Figure 10, Figure 11**) but can be as low as 10% for a prototype print when using thermoplastics. The infill density for the fiber-polymer prints is 30% as they need to be stiff but light parts (**Figure 8, Figure 12**). This can change the time taken by a print and affect the part strength.

Print quality includes layer height and line width. Large layer heights can reduce strength and reduce visual quality while also reducing print time. Layer heights and widths are also important for bed adhesion, too small or large of a layer height can cause warping in the first layer.

Printing temperature also affects the quality of the print. A proper print temperature ensures a good flow of material through the nozzle, reduces nozzle clogs, and improves layer adhesion. Build plate (bed) temperature affects the layer adhesion of the printing material. Print speed affects the printing time, quality, and layer adhesion. Too high or low of a print speed can cause prints to fail.



Cooling

Enable Print Cooling	☐
Regular/Maximum Fan Speed Threshold	11.0 s
Regular Fan Speed at Height	0.2 mm
Regular Fan Speed at Layer	2
Minimum Layer Time	6.0 s
Minimum Speed	6.0 mm/s
Lift Head	☐

Figure 13 – *Print settings for* **Figure 8** *and* **Figure 10** *in Ultimaker Cura 5.3.0. Print cooling is an important parameter for layer adhesion [14].*

Another important parameter is print cooling. The cooling fan on the printer lets the molten thermoplastics cool to make a solid part. Print cooling is recommended for low-temperature filaments like PLA and PETG but filaments like NylonX, NylonG, and SS-polymer do not work well with this setting (**Figure 13**). This is due to the higher printing temperature of the filaments. Leaving print cooling on may cause layer adhesion issues or lead to failed prints caused by the solidification of the current layer before the subsequent layer is printed. Testing different materials will give students real-world experience in using 3D printing with novel materials.

Possible Challenges

This will be a preparatory workshop that introduces a new resource that will complement currently available additive manufacturing and machining resources for senior capstone projects. The sintering aspect will be one of the parts which may need substantial preparation and additional resources. This will also require training the TAs. Sintering also requires very high temperatures (approx. 1300 C or 2372 F) [20], which can be a safety hazard. Expert supervision and protective equipment will reduce these hazards. The students will also have to be thoroughly trained for sintering metals.

Using 98% nitric acid for catalytic debinding can be hazardous as it emits nitric acid fumes and is highly corrosive. This will require strict safety standards and equipment like fume hoods, face masks, heavy-duty gloves, safety goggles, etc. but can be entirely skipped if students choose to get their parts sintered by third-party vendors [19], [20].

Another issue that may arise could be the amount of material being used and the serviceability of the printers. The equipment manager will need to make sure that the printers are always in proper working condition. Some filaments may clog nozzles which require servicing the printer, the equipment manager should be able to solve these issues or provide instructions in the training.

Filaments like PA-CF and SS-polymer come at a high market price compared to more common filaments like PLA which may require setting up material usage limits for every student to avoid the resource being financially ineffective for the institution. Although this technique is great for complex geometries, it is not a replacement for conventional techniques. The feasibility of this technique is only applicable when conventional methods fail to provide an efficient solution.

Considering that this program introduces new methods and techniques for manufacturing parts, feedback from students, TAs, and faculty will be of extreme importance. This feedback should consider the learning outcome, streamlining of processes, ease of access to resources, faculty involvement, and safety. This feedback will provide the institutions with information on where they need to make the changes and add to the advancement of engineering education [5].

Conclusion

This program is meant to help students and provide additional resources for their senior design projects. Following ASME's Vision 2030 report, this program will help students gain knowledge on technologies used in the ever-changing engineering industry. This also provides a hands-on experience with 3D printing fiber-polymer and metal parts. It also involves using techniques like sintering to let students experience multiple manufacturing techniques within the 3D printing domain.

Apart from introducing students to some of the latest developments in 3D printing, this training program will also provide design for manufacturing experience to students. Students will also learn rapid prototyping and tolerancing techniques when printing with these filaments which will further improve testing and experimentation skills, which are important to succeed in engineering.

Overall, this program will help students and provide them with a resource to prototype their projects in a faster and much more cost-effective manner.

Acknowledgments

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