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THE EFFECT OF 3D PRINTING PARAMETERS ON THE MECHANICAL PROPERTIES OF MATERIAL EXTRUSION-PRINTED CARBON FIBER REINFORCED NYLON

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THE EFFECT OF 3D PRINTING PARAMETERS ON THE MECHANICAL PROPERTIES OF MATERIAL EXTRUSION-PRINTED CARBON FIBER REINFORCED NYLON

A THESIS APPROVED FOR THE

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BY THE COMMITTEE CONSISTING OF

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Acknowledgements

Anyone who has known me over the time I have worked on my thesis knows that this was something that I struggled with. This is the third topic that I have had, with the first falling through for reasons outside of my control and the second being a topic I was not confident I could take over from someone who had started the research. And because of that along with a helping of discontent at restarting my thesis over and over, this has been a process that has taken me more years than most people would give it. Through that, there have been several people I would like to thank.

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Abstract

Material Extrusion (MEx) Additive Manufacturing, particularly with Fiber Reinforced Polymer (FRP) composites, such as carbon fiber-reinforced (CFR) nylon, is increasingly used to produce functional parts. However, the mechanical properties of parts produced on widely available desktop systems are highly anisotropic and dependent on process parameters. This thesis investigates the effect of two key slicer parameters, infill orientation and the number of wall contours, on the tensile properties and fracture behavior of MEx-printed CFR Nylon 12. ASTM D638 Type V tensile specimens and custom notched-bar samples were manufactured on a desktop MEx printer. Four infill orientations (0°, 90°, 45°, and alternating 45°/135°) and two contour settings (0 and 3 contours) were tested. Tensile testing was performed using an Instron machine, with strain data captured via Digital Image Correlation (DIC). Fracture analysis was conducted on the notched samples. The results demonstrate that both parameters significantly influence the material's tensile strength and modulus. The 90° infill orientation (parallel to the loading direction) exhibited the highest tensile strength, approximately 1.8 times greater than the 0° (perpendicular) orientation. The addition of three wall contours consistently increased the maximum load and stress at failure across all infill directions compared to samples with zero contours. Fracture analysis of notched bars confirmed that failure paths followed the weakest direction, parallel to the infill lines, a behavior that was mitigated by the inclusion of contours. This study quantifies the significant impact of infill and contour settings on the mechanical performance of desktop-printed carbon fiber nylon, highlighting the critical importance of design-for-manufacturing in MEx and the consistency challenges of hobby-level equipment for engineering applications.

Chapter 1: Introduction

ISO/ASTM 52900 defines additive manufacturing as the process of joining materials to make parts from 3D model data, usually layer upon layer[1]. This differs from subtractive manufacturing and formative manufacturing methodologies, which reduce or reshape materials. This comes with both benefits and drawbacks, which should be considered when selecting a method for manufacturing a component. In general, since additive manufacturing involves joining materials and building a part layer by layer, the resulting part's properties are inherently anisotropic.

Additive manufacturing is rapidly being adopted by the manufacturing industry for its process flexibility, often achieving geometries that are not possible with traditional manufacturing. It also offers significant benefits for small-run manufacturing, especially for prototyping, due to the negligible cost of fixturing and setup time compared to many traditional methods.[2-5] With these benefits, many industries are even utilizing additively manufactured parts as components in completed assemblies. More and more research is being conducted to investigate and quantify material properties associated with additively manufactured parts, with the aim of better understanding the limits and safety factors required for the qualification of those parts for use in commercial products.[6-10]

The ASTM standard specifies seven categories of additive processes, which will be covered in the sections below. These seven categories often share some overlap in terminology, which will be covered here, before discussing the specifics of each technology.

1.1 Binder Jetting

At its most basic, binder jetting is a process in which a powdered material is spread in a layer across the build envelope, then a print head traverses it, depositing a liquid binding agent to form the 2D shape desired for that layer. Upon completion of each layer, the build platform drops down by the layer height, and a tool spreads more powder across the previous layer, and the process repeats.

The Z axis of a binder jet printer is usually a flat plate at the bottom of the build envelope, which lowers down each time a new layer is added. Because this plate moves independently of the walls of the build envelope, a seal is required to ensure that powder does not leak into the mechanism for the Z axis and to ensure the integrity of the powder cake at the top. The X and Y axes are the drive directions for the print head which deposits the binding agent, and are most commonly standard X and Y gantries, similar to an office printer.

The powder spreading tool, often referred to as a recoater, pushes a small buffer of extra powder ahead of it, which diminishes as the powder fills the build envelope, and the excess is deposited into a waste reclamation area beyond the build envelope. Because powder is deposited onto the build envelope all at once, the area nearest to the feed area will fill up, with the waste side containing gaps if powder is underfed. An important parameter to dial in for efficient material usage is the amount of powder to feed into each layer to prevent short feeding and minimize powder waste.

The powder supply area of the binder jet process is often handled in two different ways. The first method for introducing powder to the recoating tool is to provide a supply chamber on the side with a similarly sized platform to the drop-down platform in the build envelope. By raising the feed platform slightly more than the layer height, a known amount of powder can be swept up by the recoater and deposited over the envelope. By raising the platform, a greater or lesser amount, the amount of powder can be modified. The second method for powder application uses hoppers above the build chamber, with rollers that deposit a known amount of powder per rotation in front of the recoater. Hopper-based printers often need to introduce vibration or an air-based "fluidization" effect to ensure consistent powder flow, as powder at the bottom of the hoppers can compact, leading to uneven powder distribution.

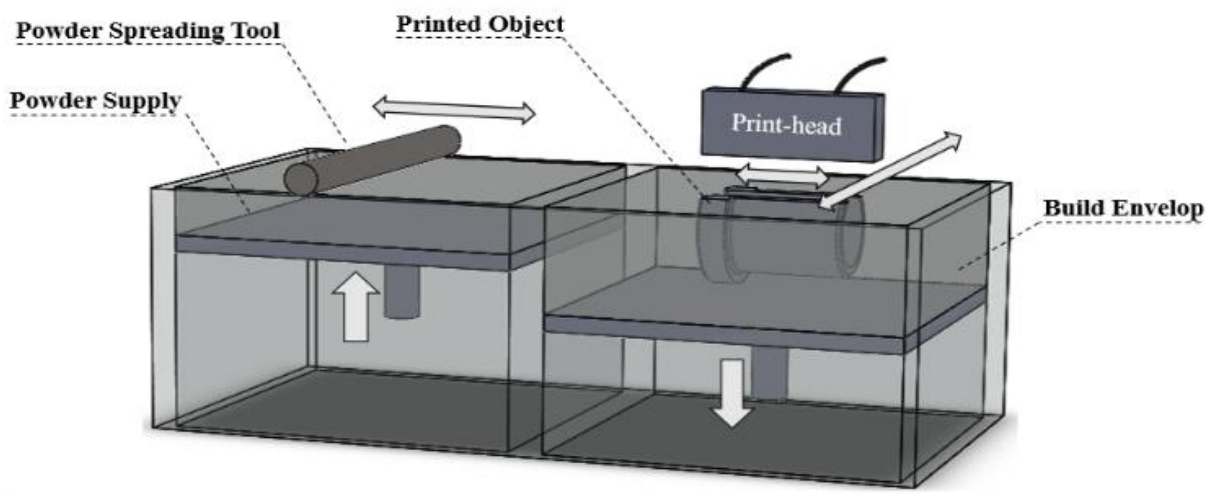

Figure 1: Binder Jet Layout[11]

1.2 Directed Energy Deposition

Directed Energy Deposition (DED) is a metal-based additive manufacturing process in which metal is applied to a surface using an external energy source, causing the metal to melt and solidify in place as it is deposited. Directed Energy Deposition has two primary material delivery methodologies, which split the technology into two distinct subcategories. The first material application method is powder fed, which is traditionally only performed with a laser-based energy source. This is commonly referred to as Laser Additive Manufacturing (LAM-DED). The other material application method is wire fed, which can be performed with lasers (Wire and Laser Additive Manufacturing, WLAM), plasma or electrical arcs (Wire and Arc Additive Manufacturing, WAAM), and electron beam (Wire and Electron Beam Additive Manufacturing, WEAM).

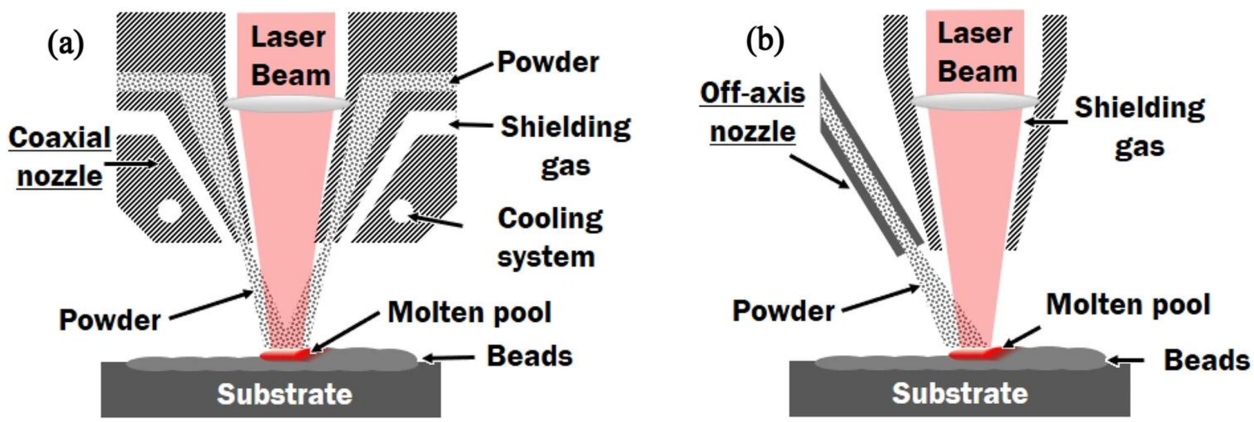

Figure 2: Powder-Based DED[12]

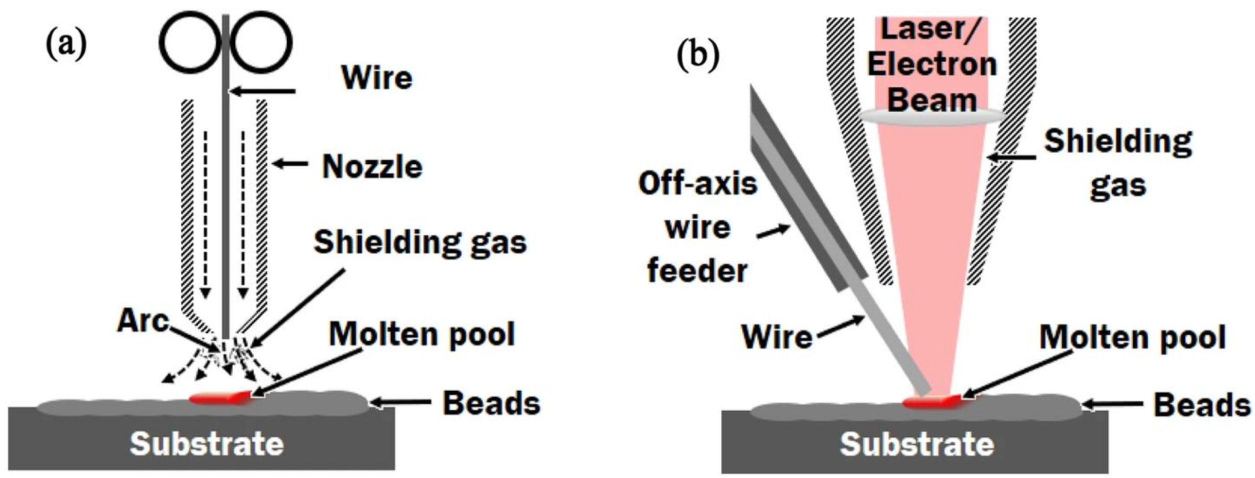

Figure 3: Wire-Based DED[12]

Regardless of which material application methodology and energy source are being used, there are a few commonalities among all DED machines. The first of these is the use of an inert shielding gas, usually argon, to help ensure material is directed correctly and remove any byproducts that may be expelled during the melt process. Another universal feature is the use of an enclosed and sealed build chamber. This helps contain byproducts from the melt pool, contain the inert gas, isolate any flare-ups caused by reactive metals, and protect the surroundings from the energy application system.

An important feature of DED machines is that the applied material and the substrate are melted concurrently to create the melt pool. For a wire-fed machine, this material application and melting combination essentially mirrors a welding process. One big benefit of using a wire-fed system is that since the material is in a solid rod prior to melting, the material capture efficiency is close to 100%. The capture efficiency for a powder-based system is much lower. This is due to the powder being projected from a nozzle and carried on a gas jet into the energy source, then carried to the surface as many small molten droplets.

DED processes can utilize a wide variety of metals. Common metals are titanium, steel, cobalt-chrome, and aluminum, but many others can be used as well. For powder-based DED, disparate metals can be applied simultaneously as needed to modify the material on a layer-by-layer basis, if needed, opening up options for interesting material properties in finished products. Wire production for use in DED is very similar to that used for welding and is a well-established process. Powder production for metal additive manufacturing is newer and requires significant process control to produce usable powder. Powder size, shape, and consistency are all vitally important to powder-based additive processes, as these affect flowability and melt speed. This can be achieved in a variety of ways, through mechanical means, atomization, or chemical means.[12]

1.3 Material Jetting

Material Jetting is a photopolymerization additive process where droplets of material are selectively deposited to create layers. On the print head, an ultraviolet light emitter is used to cure the deposited material before the build plate lowers, and another layer is deposited on top. Because Material Jetting is a liquid deposition method, the viscosity of materials is important to ensure that it can be deposited easily, but also that they retain enough stability to be cured correctly. To handle this, many materials are heated to between 30 and 70 degrees Celsius prior to deposition to decrease their viscosity and allow for material flow during deposition. During deposition, the material is exposed to cooler air and the cooled surface below it which then helps increase the viscosity to keep the material in place until it can be cured. Since parts are cured by UV light as they are deposited, material jetting actually benefits from tighter part grouping during the printing process, as this results in parts getting extra curing time per layer enhancing their dimensional accuracy.[13]

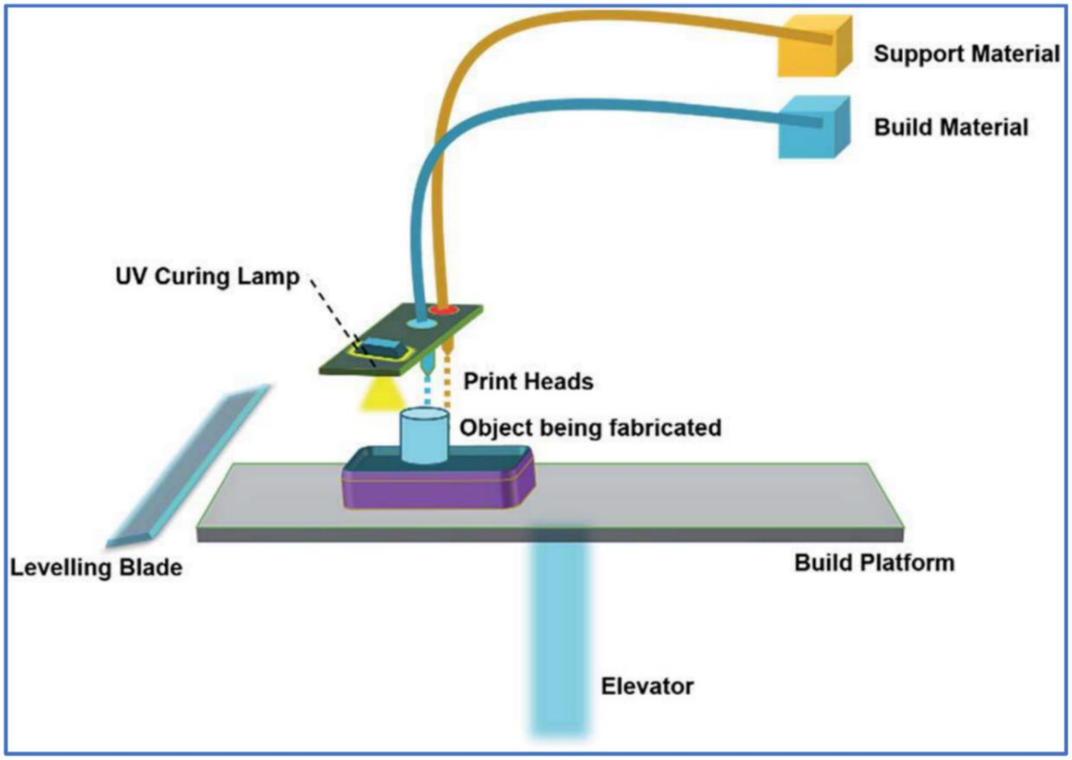

Figure 4: Material Jetting Layout[13]

1.4 Powder Bed Fusion

Powder bed fusion (PBF) can be thought of as a combination of features from DED and binder jetting. It is a process in which layers of powder are placed in a build chamber, and then those powders are fused or sintered together with heat into layer shapes that combine to form the overall part. PBF uses the material distribution and general machine setup of binder jetting and combines them with the energy-application methodology of DED machines, along with the powder requirements of both.

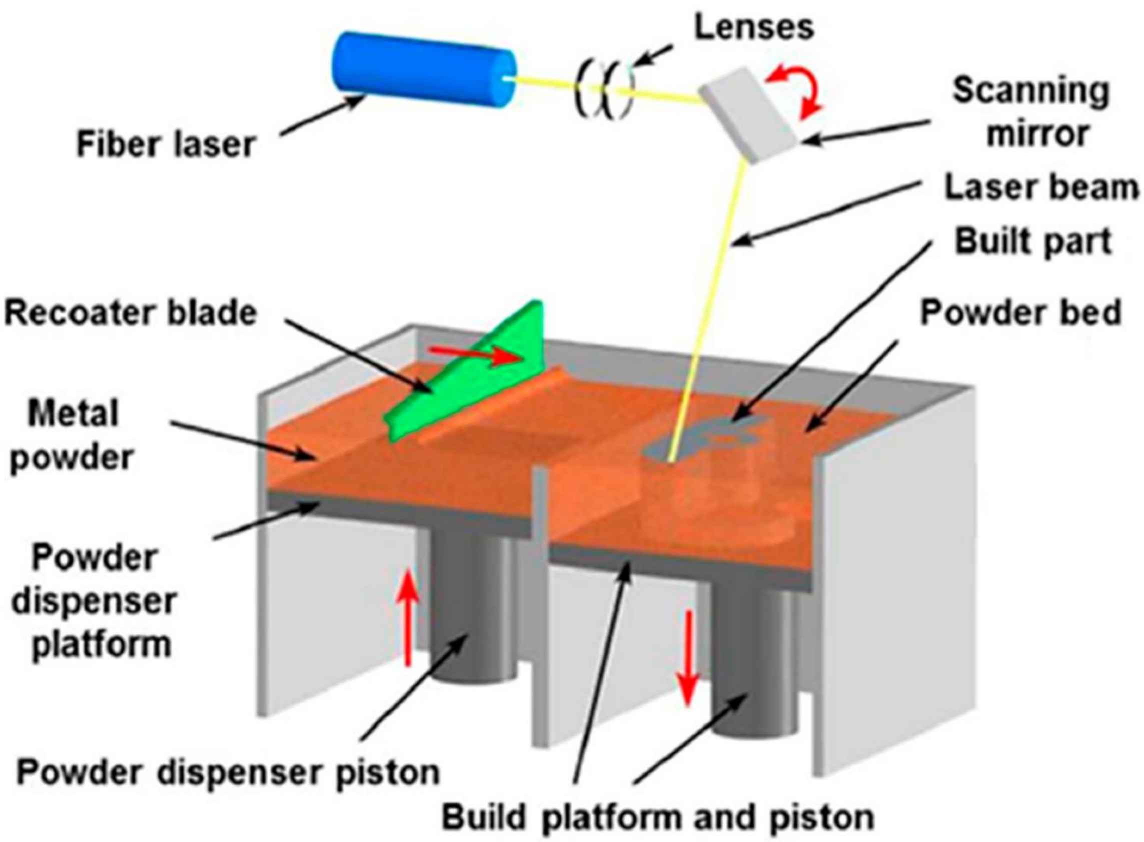

Figure 5: Powder Bed Fusion Layout[14]

PBF primarily uses one of two classes of materials, metal or plastic, and the process varies slightly depending on which is used. The powder reservoirs, either hopper-fed or riser-platform based, will be mostly the same. The use of a recoater to spread and flatten new layers of powder will also be similar, as will the use of a heated build chamber, an inert atmosphere, and the laser. This covers the makeup of a plastic machine. When using plastic, internal stresses are much lower when the material is sintered, so the powder itself is sufficient to insulate the printed layers, preventing curling and holding them in place. Because of this, plastic-based PBF often lets you add parts on top of each other in the material cake, with only a small amount of powder between them to keep them separated. The sintering process for plastic also does not produce as much cast-off residue and airborne particulates. When using metals, internal stresses are much higher; therefore, the parts being manufactured require a significant support structure attached to the base of the build chamber to prevent them from moving and curling before they can be heat-treated to relieve the stress. Since the parts must be attached, a sacrificial build plate is installed to sinter to, after which they can be machined smooth for reuse. Additionally, since the parts require supports, the ability to manufacture parts above others in the build cake does not exist. Lastly, because sintering metal creates particulates during the melting process, machines often have a flowing layer of inert gas over the area being sintered, pulling condensate into a filter to trap it for disposal.

1.5 Sheet Lamination

Sheet lamination is the combined name for ultrasonic additive manufacturing and laminated object manufacturing. At its most basic, Sheet Lamination is the process by which entire sheets of material are bonded together, and some form of trimming or postprocessing is performed to either trim layers individually as the process goes on, or at the end once all layers are bonded. Of the 7 primary Additive types, it is the one with the least information and research.

Ultrasonic Additive Manufacturing (UAM) is primarily a metal AM process, where sheets or ribbons of metal are subjected to ultrasonic welding to affix them to each other. This generally requires that the entire part be postprocessed upon completion into the required shape. This method can enable bonding of different metals for layered compositions and has a low energy requirement, since melting is not required. The process for binding the materials uses a sonotrode that rolls over the layers of metal to bond them and provide a clamping force against the base plate of the machine, and a set of grips on the end to provide a tensile force, if needed for the material.[15]

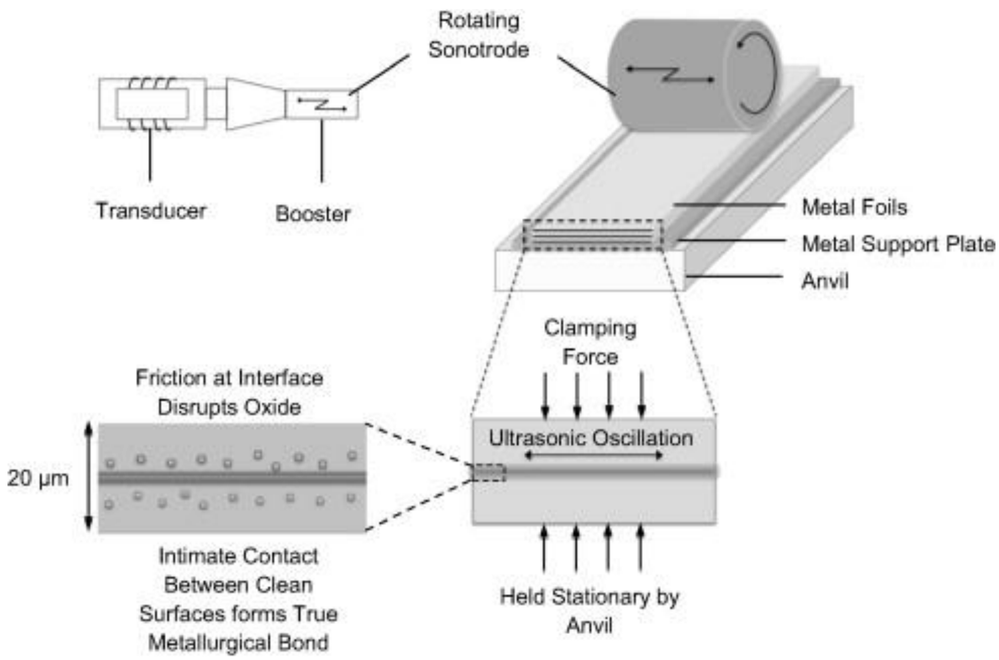

Figure 6: UAM Layout[16]

Laminated Object Manufacturing most commonly features paper as its use material and a heated roller to cure the adhesive between layers. Paper is either supplied on a continuous roll or applied in sheets for each layer. Because of the accessibility and relatively inexpensive nature of paper, Laminated Object Manufacturing was one of the first additive processes and has one of the lowest overhead costs. Since the objects made on this process are traditionally paper and adhesive, they are not suitable for structural purposes. Laminated Object Manufacturing also often trims in process, with lasers or a cutter trimming layers out and dicing up extraneous waste for ease of removal.[15]

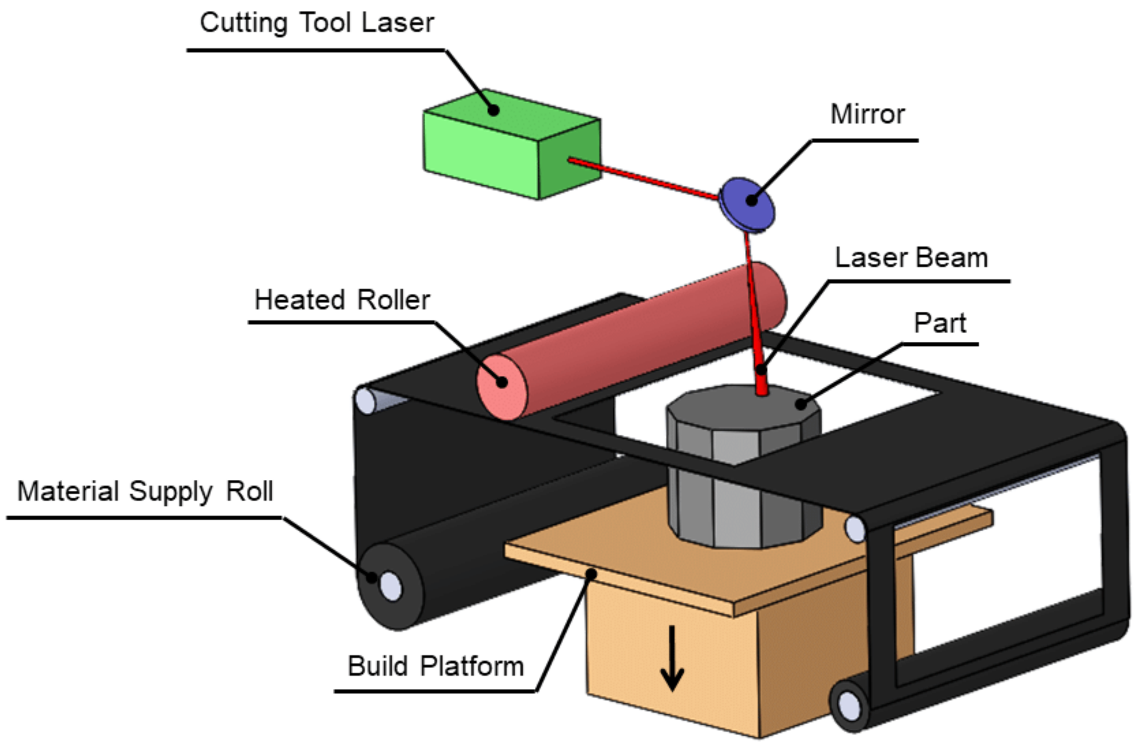

Figure 7: LOM Layout[17]

1.6 Vat Polymerization

Vat Polymerization (VP), sometimes referred to as vat photopolymerization, is an additive manufacturing technology that uses liquid resin which is cured by a light source to create a solid. As the name suggests, the primary feature of a VP machine is a vat of resin, which the build plate lowers into, with the entire structure usually enclosed in a material that blocks the light wavelengths that would cure the resin. The laser/light emitter can be located in two different places. When the laser is located below the tank, the build plate lowers until there is a single layer of resin between the tank and the bottom of the build plate, and then the laser scans the layer onto the bottom of the build plate to cure the resin. The build plate will lift by a single layer, and this will be repeated. The other location for the laser is above the open top of the vat. In this situation, the build plate will lower to just below the resin level so that a single layer can be cured on top of the build plate, and the build plate can lower again and repeat the process.

VP manufacturing speed is determined by how quickly the resin can polymerize and how much polymerization is required to complete a build. In the service of print speed, complete curing of resins is not required. Many final products are post-processed by further curing with UV light to enhance material properties after residual resin is removed from the exterior of the part.[18]

Vat polymerization is one of the two additive manufacturing processes that is most approachable at a hobby level, along with material extrusion, because the system can be self-contained within the footprint of the vat, the form factor for the printer can be extremely friendly for desktop sizes and an entry level machine can be bought for under $220.

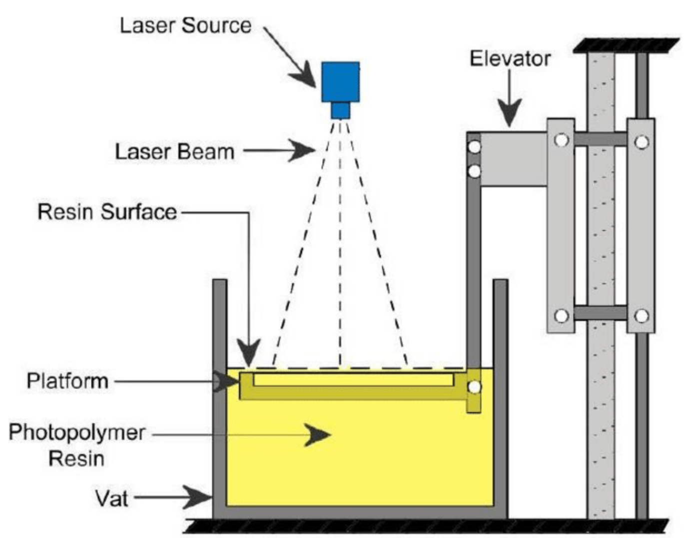

Figure 8: Vat Polymerization Layout[19]

1.7 Material Extrusion

Material Extrusion (MEx) is a process where a material feedstock is fed through a heated printhead and extruded in a molten bead, which solidifies after extrusion. Other common names for material extrusion are Fused Deposition Modeling, a trademark owned by Stratasys, and Fused Filament Fabrication. As this is the process that this paper used for manufacturing samples, the background covered on Material Extrusion will be more in-depth than the other additive processes covered above. Material Extrusion is the most accessible and common additive manufacturing technology, with systems ranging from hundreds of thousands of dollars for some aircraft-certified machines to less than $100 for basic used machines. Material Extrusion systems are even reasonable to source components for and build from scratch, with dozens of designs available online, along with bills of materials and a dedicated community. These machines are used to create parts ranging from one-off household fixes to components certified to fly on aircraft to active research in the biomedical field. At the most basic, a material extrusion system only has a few components. The machine requires a printhead to direct the material (and melt it as necessary), some sort of motion axes to control how the print head moves, and a build surface to print on, as well as a source of material.

The most common materials used in Material Extrusion are all polymers. Because polymers are such a broad category of materials with diverse material characteristics, this leaves a lot of room for variation in properties and print parameters. In addition to pure polymers, it is becoming more common to incorporate additives into polymers to modify their properties, such as graphene, carbon fibers, wood fibers, or metal powders [20]. A selection of the most common materials is below.

Polylactic Acid (PLA) is a biodegradable thermoplastic. It has a low printing temperature (between 160°C and 230°C) and does not require a heated print bed. It is also nontoxic, inexpensive, and has reasonable hardness and strength. This combination of factors makes it the most widely used material available, as it can be used by even the most basic 3D printers[21].

Acrylonitrile Butadiene Styrene (ABS) is one of the first materials used for Material Extrusion. It is also a low-cost material and features high temperature tolerance, wear resistance, and impact resistance. However, because it has a higher temperature tolerance, it requires a higher printing temperature (215°C to 250°C), which necessitates a heated print bed to reduce warping during cooling [21].

Polyvinyl Alcohol (PVA) is a water-soluble material with a low printing temperature (160°C to 230°C). It is a very common support material, used to hold up sections of a print then dissolved away afterwards[21].

Polycarbonate (PC) is a material that is both rigid and resistant to high temperatures. PC has a printing temperature between 200°C and 280°C, and requires a high bed temperature, between 80°C and 100°C. Because of these printing requirements, PC is often the top end of what hobby-level printers can achieve, often requiring modifications to achieve quality prints [21].

Nylon is one of the most commonly used materials for functional parts due to its strength and durability. Nylon does suffer from high moisture absorption and requires a high print temperature (230°C to 265°C) and a heated build plate of at least 60°C[21].

Polyetheretherketone Polymer (PEEK) is the highest end (rephrase that) material on this list. PEEK printing is not common outside of manufacturing industries due to its high print temperature (340°C to 440°C) which in turn generally requires a heated build chamber and build plate, and specialty high temperature electronics. PEEK does feature excellent mechanical properties, and it is common in high performance environments[21].

Thermoplastic Elastomer (TPE) is a flexible thermoplastic. It has a relatively low print temperature (180°C to 230°C) and does not require a heated bed. Because of this, it is one of the most common materials used for any application that requires a flexible component[21].

The extrusion head or print head is one of the most important parts of the entire assembly. The print head is the location where material is extruded in a liquid form to create the lines of material that build up into layers and ultimately create the finished product. As this is the component that extrudes the material, one of the primary components in the print head is a nozzle or orifice that controls the width of the material extruded to create the layer lines. The layer height of Material Extrusion machines is also affected by the orifice size/layer line width, although this can vary more than the layer line width. Generally, layer height is about half the layer width.

Most Material Extrusion machines also contain a heating element or heating block and thermistor in the print head. Material is delivered in a solid state to the print head, where it then has to be melted so that it can be extruded through the nozzle. For most machines, the material is delivered in a consistent diameter filament wire, with the heating element bringing the nozzle to a known temperature to melt the filament as it is forced through the nozzle.

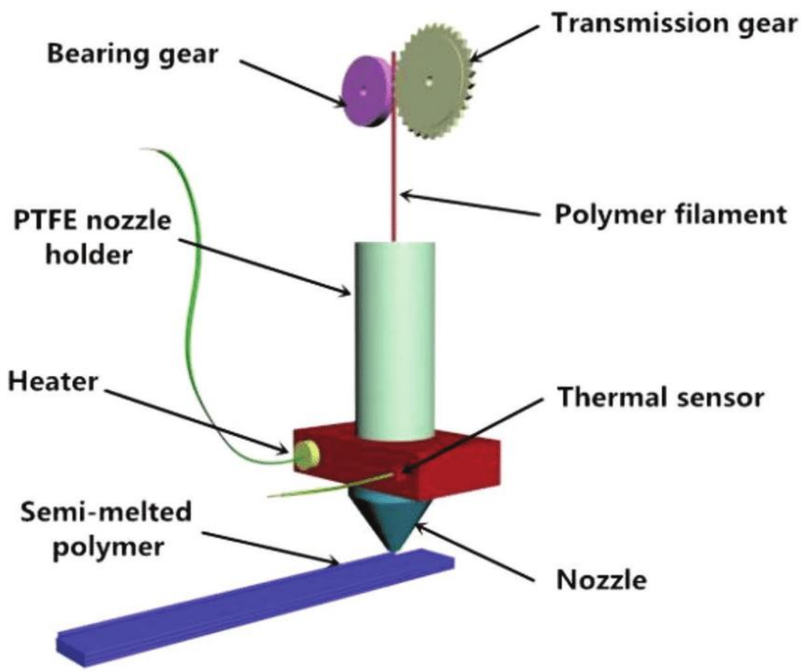

Figure 9: Filament MEx Print Head[22]

The other format of material used for Material Extrusion is pelletized material, which is hopper-fed into a rotating screw inside a tube that is being heated by the heating element. This material is forced forward by the screw and melted by the heated tube so that it can be delivered to the nozzle in a melted state.

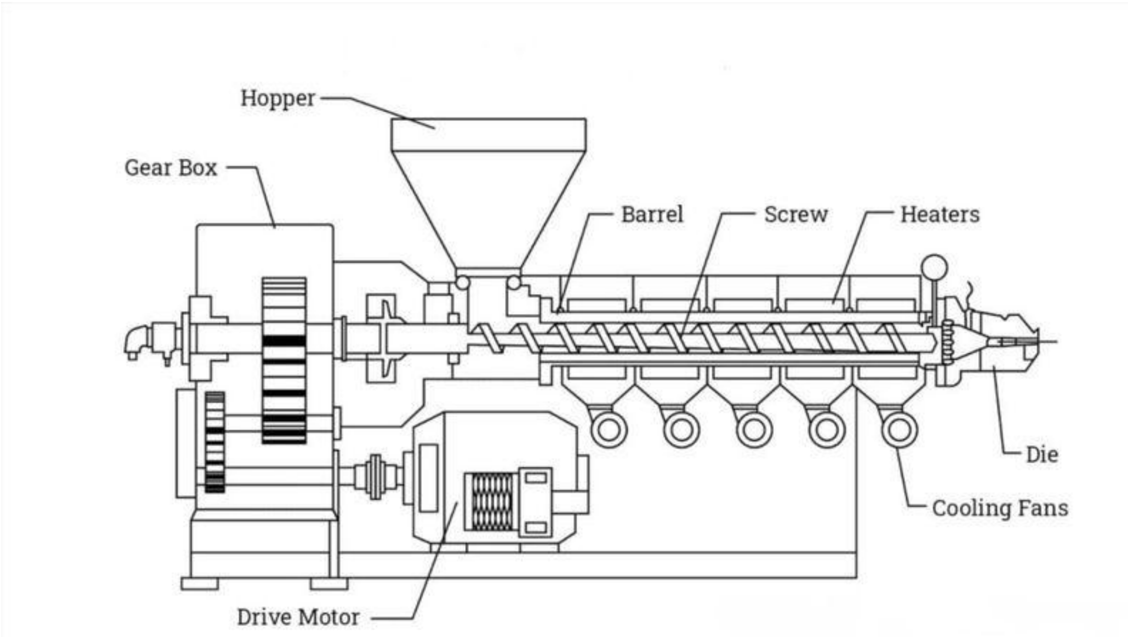

Figure 10: Pellet MEx Print Head[23]

The next common part located on the print head is the material drive component. As noted above, the material for pellet-fed machines is driven by the screw in the print head. For filament-based machines, the material is instead driven by a small electric motor that feeds the material forward into the nozzle. This motor can be located on the print head (direct extrusion) or on the machine frame and runs through a flexible tube to the print head. This style is called a Bowden Extruder, and the tube is called a Bowden Tube or Teflon Tube. Extruders on the print head are usually simpler, as the material is driven directly into the nozzle, but the added weight of the print head makes printing slower, as the print head takes longer to accelerate and decelerate when moving.

The last component commonly found on the print head is a part cooling fan. Part cooling fans are used to control the solidification rate of material after extrusion. For geometries that have a small XY cross-section, material may not fully solidify prior to the extrusion of subsequent layers. This can cause poor print quality, which can be offset by using a part cooling fan to aid in the solidification of layers as they are deposited. Another benefit of part cooling fan usage is to increase the overhang tolerance and angles by aiding in solidification before the material can droop. Some materials, specifically higher temperature materials without a heated build chamber, struggle to deposit successfully with a part cooling fan, due to curling from the cooling rate and the shrinkage of the materials.

Outside of the printhead, there are several other important components in a Material Extrusion machine. The motion system controls the motion of the print head relative to the print surface and thus is potentially the component that has the greatest influence on the final part after the print head that extrudes the material. There are several types of motion systems that are used in Material Extrusion machines, but a cartesian gantry system is by far the most common. Gantry systems can come in several styles as well, but at their simplest a gantry-based system involves at least one gantry axis which has a driven shuttle on attached to the print head, allowing the print head to traverse that axis. The most basic, non-industrial machines generally only have a single gantry axis that traverses the “X” direction for the machine. This is cantilevered off a “Z” axis, which is another shuttle that travels up and down rods vertically, driven by a screw, which often makes them referred to as “XZ” printers. Lastly, the print surface or build plate is on its own axis that moves perpendicular to both, making the “Y” axis. This style of printer is commonly referred to as a “bed slinger” as well, as the print bed exists on its own axis and print motion in the Y direction requires the bed to be slung back and forth. A step up from this style uses a second set of rods and driving screw across the X gantry to support the gantry better and provide more stability.[24]

Figure 11: Prusa Mini+ XZ Cantilever Machine[25]

Figure 12: Creality Ender-3 S1 Pro XZ Machine[26]

The next step up from a single-axis gantry is the two-axis gantry, which is generally referred to as “core XY” machines. As the name implies, this format of machine has an X gantry and a Y gantry that work together to move the print head across the entire material extrusion plane. This method provides even better stiffness and tighter control of the print head, but is more costly to produce and requires a larger frame with support structures in all four corners of the gantry area. The Z axis on core XY machines is attached to the print bed rather than the gantry system and raises and lowers the print bed to match the height of the XY gantries. Because core XY machines already have structural posts in all four corners, enclosing the build chamber is common, as it requires little additional material or design. This is the design that most commercial printers conform to.[24]

Figure 13: Creality Ender-5 S1 Core XY Machine[27]

Beyond gantry-style Cartesian machines, there is another type of motion system that is sometimes seen: a “delta” printer. Delta printers function by having three vertical posts set around the build area. Each of these posts has a drive system to move a shuttle up and down the post, and an arm that reaches from the shuttle to the print head. Each of these shuttles can move up and down independently, allowing the print head to be moved freely in between the posts. These machines are generally fast and high quality, but have much more limited build area compared to machine size.[28]

Figure 14: Trilab DeltiQ 2 Delta Machine[29]

The motion system is what allows the print head to be where it needs to be to extrude material in the correct space. However, a Material Extrusion machine still requires something for the first layer of material to be deposited onto, the print bed/build plate. An adequate build plate is another highly critical portion of the overall machine. Poor adhesion between deposited materials and the build plate is one of the most common failure modes in Material Extrusion parts. There are two styles to print beds for Material Extrusion, a bed where material is deposited directly onto the surface of the bed and a version which has a removable layer on top of the base that is interchangeable. Machines where material is deposited directly onto the baseplate of the print bed are less common and require much more maintenance if the build plate is damaged.

Removable print beds are much more common, as they allow the user to change the print surface quickly for maintenance, use different materials based on the plastic being deposited on it, and the ability to take a completed part to a benchtop to remove it from the build surface rather than working inside of the confines of the machine. This can be handled in a variety of ways. The most popular method for hobby level machines is to attach the build surface to the base of the print bed magnetically. It is a relatively inexpensive solution, but can cause variance in the level of the build plate. Another common method is simple mechanical retention, through clips or screws. This is slower to change out, and often requires the print surface to be stiff to maintain shape across the center of the surface where fasteners would interfere with the print surface. The last method that is commonly used is what many commercial printers use. They rely on a vacuum sealing system, where a build sheet of the material that the first layer will be deposited on is placed on the base of the print bed over a grid of shallow, machined channels. A vacuum pump is turned on, pulling the air out of these channels and suctioning the build sheet down. This negative pressure differential is kept on while the printer is active, holding the build sheet flat and in place. This is a very effective method, as the base of the print bed can be robust and stiff enough to ensure that the build sheet stays flat and temperature variance does not overly affect the surface.

Depending on the type of print bed used, there are often several different materials they can be made from. Most non-removable build plates are made from tempered glass, sometimes including a coating on top to aid adhesion. Glass build plates are generally cheap, easy to make, and are thermally stable to prevent warping during changes in temperature. Coated spring steel build plates are very common for removable build plates in hobby level machines and are usually coated with polyetherimide (PEI) in either a smooth or textured variety. PEI coatings create good bonds with deposited plastic, reducing the need for adhesive aids. Smooth PEI coatings adhere better, but the textured PEI plates are easier to remove cooled parts from. There are other, less common materials and coatings used, such as G10 and polypropylene, but they are primarily used in niche situations or older model machines. Lastly, vacuum suction build sheets are usually made of plastic, and the type used depends on the materials and temperatures involved. For most materials that aren't high temperature (like PEEK), a polycarbonate build sheet is used. The downside of these plastic sheets is that the model material often adheres to these materials too well and will not come off. These machines often also use support material that breaks away or dissolves from the model material to aid in removal. In addition to the material that a print bed is made from, some people keep adhesion aids with their printer to apply to the build sheet to aid adhesion of the first deposited layer. Common items used as adhesive aids are glue sticks, painters' tape, and hair spray.[30]

A common addition to the print bed/build sheet system in a printer is a heated build plate. Heating the build plate improves adhesion and print quality by preventing the base layer from cooling fully, reducing warpage during the print. The heated build plate will also have a minor effect on other layers, as the heated air from the build plate rises over the part. However, without an external heat source to keep the surrounding area warm as well, this effect can quickly diminish. Heated build plates are necessary for many higher temperature materials, such as PEEK and Nylon.[30]

Moving beyond the motion system, the last feature common to every Material Extrusion system is a controller. Most Material Extrusion systems use a small control board built into the machine, often attached to minor peripherals that allow monitoring of process parameters and enable the user to interact with files and assert some manual control over the printer components, or even Wi-Fi capability. The significant features of a control board will be the firmware that is loaded onto it (either open-source firmware for many hobby-level printers or closed-source proprietary software for many commercial-grade machines) and the microprocessor included on it. The firmware allows the machine to parse G code, control motors, read thermistor values, modify output to heating elements, perform subroutines such as bed leveling, and accept external files for manufacturing. The microprocessor is simply the device that performs all necessary calculations to enable the firmware to function, with faster microprocessors enabling enhanced performance.

The use of an enclosure around the print area, often called a build chamber, is not necessary for a Material Extrusion machine to function; however, it is highly beneficial and almost guaranteed to be included in any commercial machine, as well as many high-end hobby-level machines. Build chambers can be built into the machine or added after-market. There are a variety of benefits conferred by a build chamber with almost no downside other than the complexity of the machine and added size. One benefit of the enclosure is that it allows for increased environmental stability during part manufacturing. By minimizing air exchange with the surrounding environment, cooling for manufactured parts is much more even, and shrinkage and warping can be reduced. The introduction of a build chamber can be the difference between a material being usable and failing every time, as with Nylon. Another benefit of the enclosure is the containment and filtering of emissions from heating plastics, which can potentially form a health risk.[31]

In addition to standard build chambers and enclosures, a heated build chamber can confer even more benefits. Heating the build chamber allows finer control and greater success during printing by keeping extruded plastics at elevated temperatures to minimize warpage and providing the ability to control cooling rates upon completion of a print. Some higher-end materials, such as PEEK, are not even viable to utilize without a heated chamber due to their warping characteristics. Care needs to be taken with machines that have heated build chambers, because the heat cycles and prolonged time at temperature increase wear on components inside the heated area, and can increase preventative maintenance costs.

Another piece of equipment that isn't necessary but can be packaged with some machines is a material drying system and a desiccant bay to keep the material dry. Many plastics used in Material Extrusion absorb moisture from the air. When the material is melted for extrusion, the moisture heats to the point that it evaporates and expands. This causes smooth extrusion lines to become inconsistent, affecting the quality of the print. To counteract this, material is often shipped sealed and dry. However, if material is partially used and then stored it can begin to absorb moisture. Desiccant boxes are a good storage solution for still dry material, but if moisture has already been absorbed, an oven is used to heat the material enough to evaporate any moisture, before the material is moved to the dry box. Desiccant systems can be separate or can be included bays inside of the machine.

While it is not a part of the printer system itself, slicer software is another important piece of a functional Material Extrusion machine. The goal of slicer software is to take a 3D model that is to be manufactured and convert it into a G code that is readable by the printer, often including all relevant codes for turning on peripheral objects such as heaters and sensors, as well as interjecting any snippets of code that may be required mid run, such as purging extra material, printing support structures or producing print assistive structures like cooling towers. Slicing software for most hobby-level printers is general and can produce files for a variety of manufacturers. Software such as Cura (made by UltiMaker) and PrusaSlicer (made by Prusa3D) have profiles for dozens or hundreds of different printers, often made by the printer manufacturer and provided to the software developer. Larger commercial/industrial printer manufacturers often have proprietary slicer software to interact with their machines, such as Insight (by Stratasys) or 3D Sprint (by 3D Systems). These slicing software also usually have a utility for minor manipulations of the loaded file prior to manufacturing, such as moving, resizing, and copying.

Proprietary software benefits from extensive manufacturer research on the included profiles, but comes at the cost of restricted freedom. These software's will only allow for the use of certain approved materials with certain, approved tips and build sheets on a list of approved machines. The research means that generally, a file can be sliced and produced with little to no tweaking and be expected to be repeatable without much interaction or risk of failure, but it does limit the allowed modifications to parameters to simple things such as the number of contours in a print, the amount of infill, and the directions of each layer of infill.

The general, open-ended software allows for extensive customization of the process, with access to hundreds of parameters that can be modified. These usually cover the same restricted list as in proprietary software, but also include many other items specific to lower-quality-controlled materials. They can even be used for working with a material that isn't used with that machine normally, such as material retract distance at the nozzle when not extruding, over-extrusion amount, and temperature controls. This freedom comes with less repeatability and the potential to have to tweak values from a known working set if a material manufacturer or the printer environment changes.

Chapter 2: Methods and Equipment

2.1 Materials

The material used for this research was Matterhacker's brand NylonX filament, which is a Nylon 12 (polyamide 12) filament with approximately a 20% by weight chopped carbon fiber suspension extruded to a filament diameter of 1.75mm. A table of material properties from the vendor is provided below in Table 1.[32] This material was already in use by the University of Oklahoma for research purposes at the start of this project so the roll of filament used was no longer vacuum sealed.

Print Temperature	250-265°C
Print Speed	25-35 mm/s
Bed Temperature	60-65°C

Table 1: Nylon X Parameters and Specifications

As Nylon is highly susceptible to moisture absorption, a filament drier and desiccant packets were used to lower the moisture content in the filament. A Sunlu S2 filament drier was run at 65°C with the lid cracked over three 6-hour cycles to lower the moisture in the filament. Then desiccant packets were placed in the center of the spool, and the lid was sealed to keep moisture levels consistent. Filament was then fed directly from the drier box to the print head to reduce time exposed to moisture. During coupon manufacture, the relative humidity in the container was lowered to around 20%.

2.2 Printer and Accessories

For this research, a Creality Ender-3 S1 Pro machine was chosen. The Ender-3 S1 Pro is a ZX "bedslinger" style machine with several features that make it appealing for this use case. The biggest factor in machine selection was the temperature requirements for printing NylonX. This version of the Ender 3 is among the least expensive machines that can achieve the required print head and bed temperatures without modifications. Out of the box, this machine can achieve 300°C hot end temperatures and 110°C bed temperatures. Additionally, this machine features an automated bed leveling system that uses 16-point mesh compensation to improve layer consistency, a spring steel PEI magnetic build plate to enhance adhesion, and direct extrusion. The tip provided with the machine was a 0.4mm brass tip, which will not withstand the abrasion of chopped carbon fiber extrusion. This tip was replaced with a 0.4mm hardened steel nozzle. A more detailed list of parameters is provided in Table 2.[26]

Build Volume	220 x 220 x 270mm
Print Speed	<160mm/s
Layer Height	0.1 - 0.35mm
Filament Diameter	1.75mm
Nozzle Temperature	Up to 300°C
Print Bed Temperature	Up to 110°C

Table 2: Ender-3 S1 Pro Specifications

To further aid adhesion, the nylon was fed directly from the desiccant chamber to the print head, and both were placed inside a large printer enclosure tent. The printer enclosure tent ensured that the print environment stayed at a consistent temperature and free of drafts, which might cause shrinkage and curling. The enclosure was made of silicone composite fiberglass coated on the inside with an aluminum film.

2.3 Testing Equipment and Methods

The above printer and material setup was used to produce tensile bar samples per ASTM 638: Standard Test Method for Tensile Properties of Plastics[33]. Specifically, type V samples were manufactured to reduce material costs and increase manufacturing speed. An engineering drawing of the sample is provided in Appendix A. In addition to the "dog bone" style tensile samples, a set of notched bar samples was also created to guarantee a failure area, and to compare the importance of the number of contours, as this design had room for more variance. An engineering drawing sample of these is available in Appendix B.

Two pieces of equipment were primarily used to test these samples. An Instron (Model: 5969) mechanical testing frame was used to load test the sample coupons until failure. Samples were gripped in their clamping area by a set of knurled clamps, and the load sensors on the Instron were zeroed out prior to testing. Measurements for the width and height of the gauge length were taken per individual sample prior to tensile testing and fed into the Instron to allow for the collection of stress and overall elongation data.

In addition, a subset of the coupons was tested using Digital Image Correlation software and a camera setup in conjunction with the Instron tensile testing machine. The ARAMIS system, developed by GOM/Zeiss, is a non-contact, optical 3D Digital Image Correlation (DIC) system used for full-field strain and displacement measurement. The system uses a stereoscopic setup of two high-resolution digital cameras to capture a series of images of a test specimen during deformation. To facilitate tracking, the specimen's surface is prepared with a stochastic (random) speckle pattern, which provides the necessary high-contrast features. As the specimen is loaded (in this case, by the Instron tester), the ARAMIS software tracks the distortion of small subsets of this pattern, known as facets, in three-dimensional space. By applying photogrammetric principles, the system triangulates the precise 3D coordinates of thousands of points on the specimen's surface for each captured image. This allows for the calculation of a full-field map of displacement and strain (e.g., major and minor strain) across the entire region of interest, providing significantly more detailed and localized strain data than traditional contact extensometers.

To allow the DIC software to detect elongation in the coupons' gauge length, the surface of the coupons facing the calibrated cameras had to be modified so that recognizable features with sufficient contrast would be visible. This was achieved by applying a thin, complete coat of matte white spray paint to the face of the coupon, and then applying a second, uneven speckled coating of matte black paint on top. This provides unique shapes and high contrast with sharp edges to maximize the image recognition in the DIC software.

Since this method uses cameras to capture minor movements in small objects at a distance, the cameras and calibration are extremely delicate. If the setup is moved even slightly, the cameras' focal lengths can no longer match. Similarly, moving the coupon closer or farther away, or even to the side, can result in data capture failure. With this in mind, all data collection with the equipment was performed consecutively without allowing for the system to be taken down and stored. Even with care taken, the system still required recalibration 3 times due to contact with the camera mounts.

2.4 Parameters for testing

Based on the materials and equipment used, several of the print parameters had a range of acceptable values. To maintain consistency across testing, once successful printing was established, all parameters other than the infill direction and contour number were locked down for the tensile samples and for the notched bars. Lots were determined by the infill direction (1 through 4), and lots were repeated for 0- and 3-contour cases. A complete parameter list of relevant parameters can be found in Appendix C.

Chapter 3: Results

3.1 Printing Inconsistencies and Warpage

Loh et al. identified 39 "problems" or common failure modes across three categories (print quality, deposition associated, and printer associated) that are common in Material Extrusion and determined that there were 60 items denoted as "causes" across four categories (printer settings, hardware, material, and CAD Model/slicer) that were responsible either individually or as part of a combination for these 39 problems. Many of these causes can result in inconsistencies between runs of the same file, causing material properties to change between components manufactured from identical print files. As the coupons for this paper were manufactured with consistent slicing and CAD modelling, the 4^{th} category (CAD issues and slicing settings) will be ignored, leaving 44 causes. Of the 44 causes listed, 11 were related to temperature in some way, and 13 were hardware/maintenance issues, making these the two most common causes of print issues and inconsistencies for Material Extrusion.[21]

Material Extrusion, at its most basic, is the process of heating a material to its melting temperature, then extruding it to solidify into a chosen layout, creating a shape. Based on this, the importance of temperature is easily seen, especially with regard to consistency and control of the manufacturing process. Temperature variance can apply to many different places in the process, however, and can appear as both a controllable and an uncontrollable value depending on the accessories associated with the equipment.

The most immediate location where temperature is critical is the printhead, where the solid material is melted and extruded. This is the most basic heating required for most Material Extrusion processes, and, by virtue of that, most machines are adequate at controlling this temperature. There is variance among equipment manufacturers, and this is one of the most frequently upgraded areas for hobbyists to focus on, as the quality of the thermocouple and heater block will vary. Once the material is extruded, it will cool in the ambient air. That cooling is far less controlled, as the amount of air movement and local temperature will affect the cooling rate significantly and potentially unevenly across multiple runs. This can be further affected by using a cooling fan on the print head, which will increase the consistency of airflow but can also cause warping issues by cooling too quickly. Other areas where temperature comes into play include the build plate temperature, the temperature of the electrical components (though that is more of a maintenance or machine factor), and even the material temperature prior to melting. Temperature is the most important parameter for quality and repeatability.

Maintenance and upkeep of the printing equipment is also extremely important to minimize differences between print runs, but, like any manufacturing process, the equipment will change and wear over time. One of the most common maintenance/machine issues, though it also touches on temperature, is the consistency of extrusion through the nozzle. Temperature fluctuations can cause clogs, but many machine factors can also be shown here. Nozzles are a consumable item for Material Extrusion machines. The orifice diameter changes as it goes through heat cycles and is worn by the material. Additionally, heat cycled material can build up inside the nozzle, causing full or partial clogs. Other maintenance issues such as failure to clean the tip of buildup can lead to material blocking the extrusion and creating a ball on the tip. Components like the drive belts and idler gear function with a moderate amount of tension on them. These user tightened components can relax as a print run either due to stretching of components or vibration of the machine or can be overtightened, both of which lead to issues. In addition to these, there are many other less common maintenance issues that can be found throughout the machine such as failing components and bad alignments.

While care was taken to eliminate as many issues as possible during manufacturing of the test samples for this experiment, some amount of variance is expected due to the nature of the equipment used for manufacturing, and the materials involved. Nylon especially is highly susceptible to temperature variations, and it was the material used for these coupons. Many issues with the printing process do not result in failed prints, but inconsistent Material Extrusion can wildly affect material parameters during testing.

3.2 Result Data

Results fall into two categories, pull test with data only collected by the Instron tensile testing equipment, and pull test from the Instron with the addition of localized strain data from the DIC. The pull test with DIC data should be more accurate because it tracks strain at the fracture location rather than over the entire length of the part, but the time and setup required did not allow every sample to be tested that way. An example of the data provided by the Instron is shown in Table 3 below. In addition to those parameters, the extension of the jaws, the load applied by the jaws, and the tensile stress are given every 0.1 seconds in an Excel table.

Parameter Measured	Value	Unit
Modulus (Automatic) : Modulus (Automatic)	337.4789	MPa
Tensile strength : Load at Tensile strength	517.3736	N
Tensile strength : Time at Tensile strength	84.4	s
Tensile strength : Tensile stress at Tensile strength	59.69466	MPa
Strain : Tensile strain (Extension) gauge length	9.53	mm
General : Specimen number (included)	1	
Specimen notes : Specimen note 1		
Specimen properties : Specimen label	7	

Table 3: Example Instron Provided Data - 3 Contours, Infill 1 Sample 7

The first data set (Instron only) contains 10 samples per infill direction, repeated for three contours and zero contours. This data set was only pull-tested, and the results given were directly derived from the load and extension data the Instron collected, as well as user inputs for gage length, width, and thickness. Results provided by the equipment were averaged for each data set, and are provided below in Table 4 and Table 5.

3 Contour	1	2	3	4
Modulus	335.054	467.889	376.555	361.547
Average Load at Failure (N)	496.147	565.438	505.700	496.887
Average Time to Failure (s)	80.540	69.730	75.030	78.956
Tensile Stress at failure (Mpa)	53.438	62.076	54.359	57.683

Table 4: 3 Contour Data Set 1

0 Contour	1	2	3	4
Modulus	240.076	534.360	246.525	262.456
Average Load at Failure (N)	300.123	546.019	344.083	365.755
Average Time to Failure (s)	86.000	75.100	109.725	117.650
Tensile Stress at failure (Mpa)	31.112	58.136	37.059	38.514

Table 5: 0 Contour Data Set 1

Based on the data in dataset 1, Figure 15 and Figure 16 below were created. These figures show the average stress and average load at failure for each paired data point (infill direction 1 for 0 contour compared to infill direction 1 for 3 contour, repeated for each infill direction pairing). This gives a good representation of how each pairing matches up, with every 0-contour coupon group underperforming its matched 3 contour counterparts.

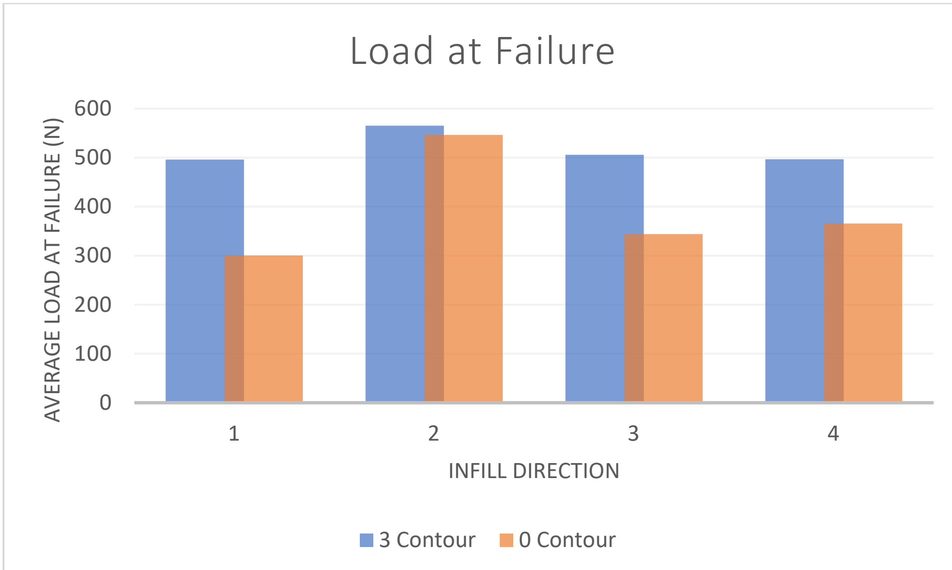

Figure 15: Average Load at Failure, Data Set 1

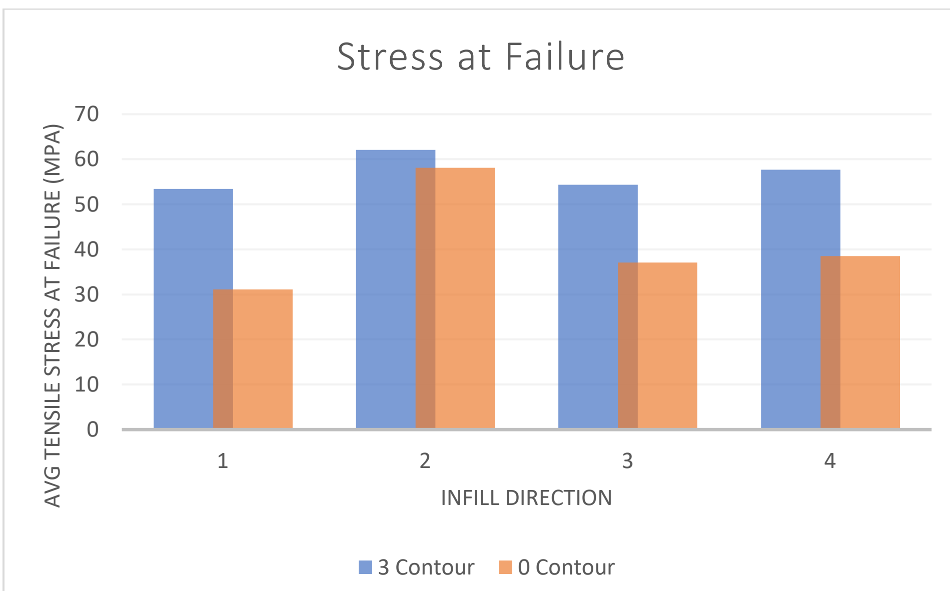

Figure 16: Average Stress at Failure, Data Set 1

The results from data set one show the importance of being mindful of the direction of load imparted to an additive manufactured part and designing with that in mind. Based purely on infill direction (the 0 contour data), an infill in the direction of load can handle about 1.82 times the amount of load that an infill running perpendicular to the direction of load, and in cases where load may not be known, alternating 45° and 135° infills can still handle loads 1.2 times higher than having a perpendicular infill.

The second data set was the result of a combination of Instron's data, collected in the same way as the first data set, but combined with DIC's much more localized deformation data to give accurate stress-strain curves. This was performed for a minimum of 3 samples per contour number and infill direction combination. The figures for that data can be found below in Figure 17 through Figure 24. The DIC process is more temperamental than a traditional strain gauge is, but it also allows for more localized strain measurement within the gauge length, as elongation is not always constant across the gauge length, especially with non-isotropic materials. Due to the more difficult data acquisition, some of the data from coupons in this data set were unusable, resulting in inconsistent numbers of coupons for each orientation and infill direction.

As can be seen across the figures using the DIC data, only the 0 contour with infill orientation 2 showed consistent tensile stress values. All other sets of DIC data had noticeable variance in their measured maximum stress. This is consistent with the data from data set which also showed variance across all the measured stress and loads but is not as apparent without graphed values to compare.

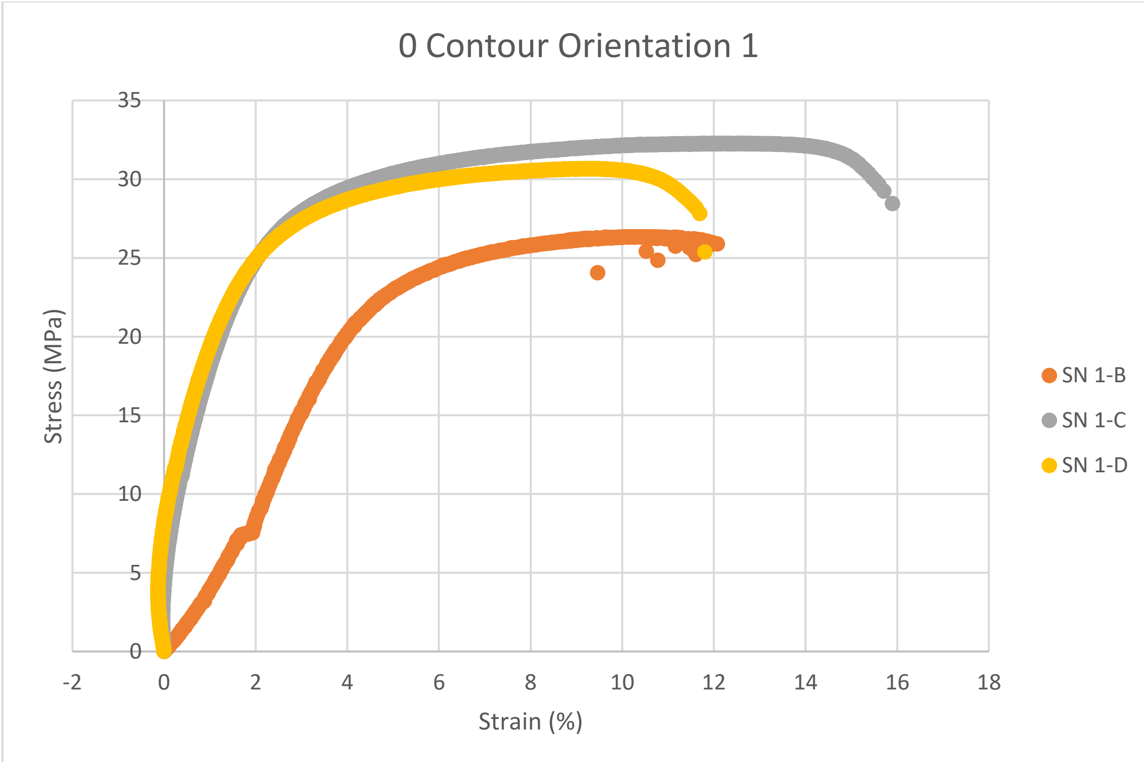

Figure 17: 0 Contour Orientation 1 Stress-Strain Curve

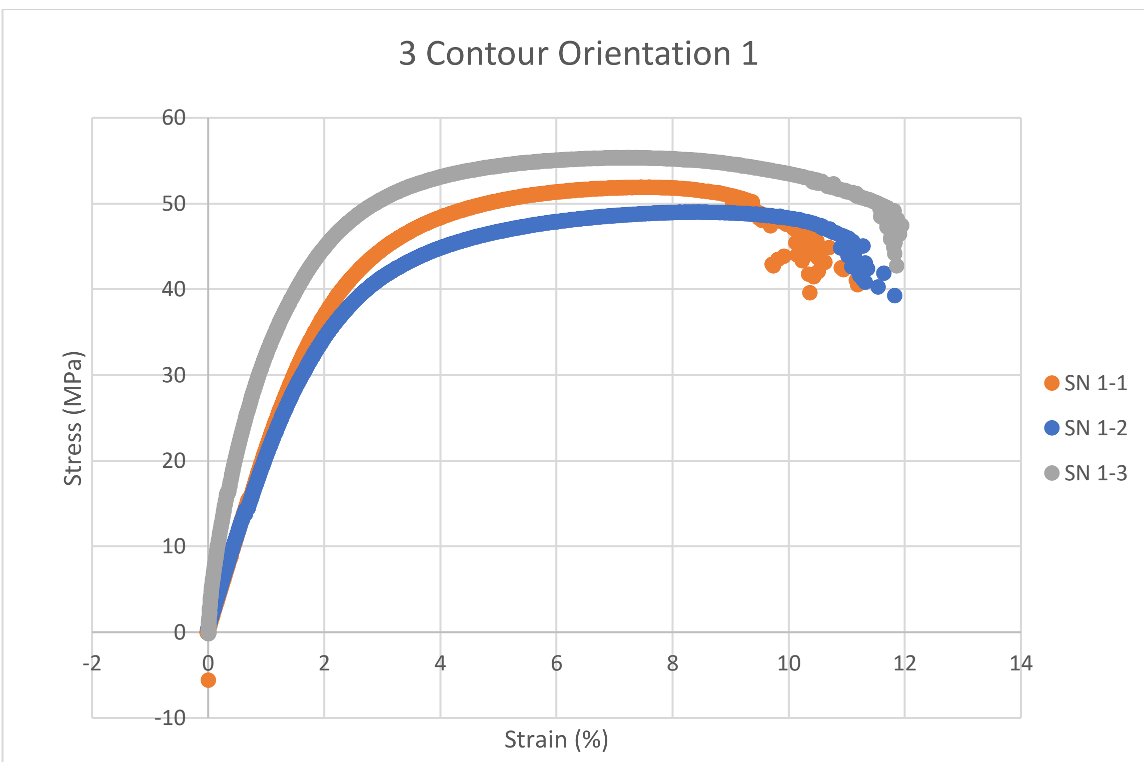

Figure 18: 3 Contour Orientation 1 Stress-Strain Curve

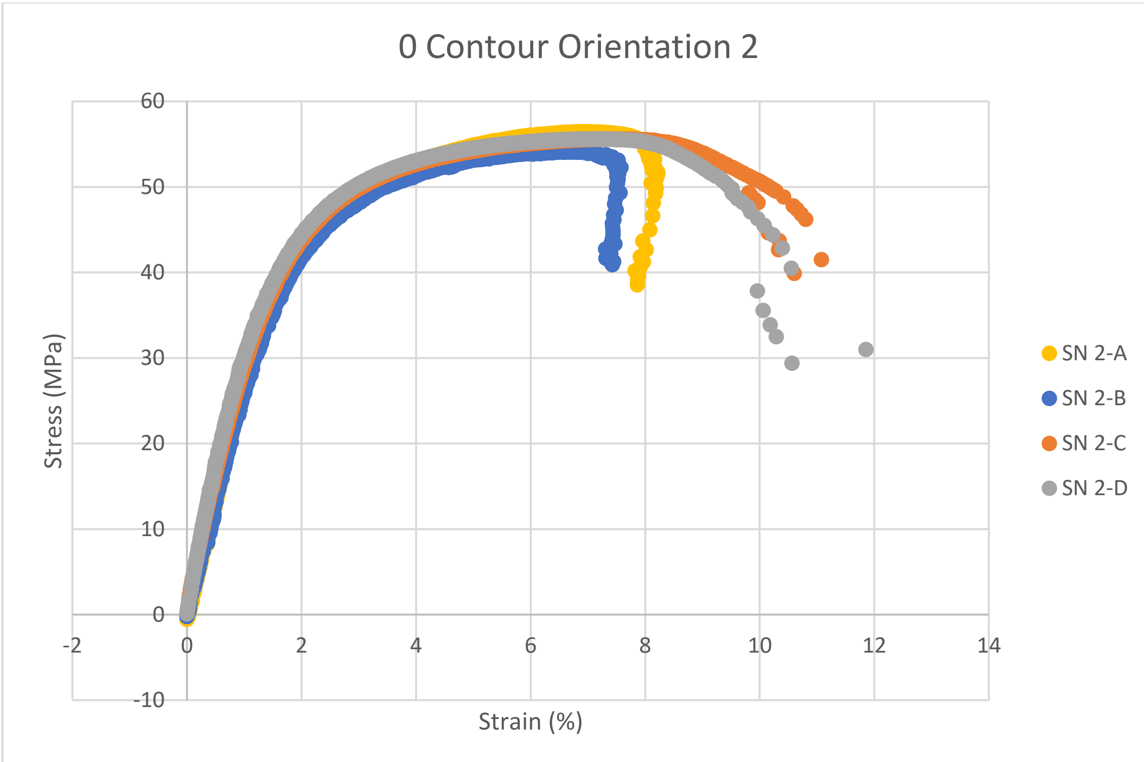

Figure 19: 0 Contour Orientation 2 Stress-Strain Curve

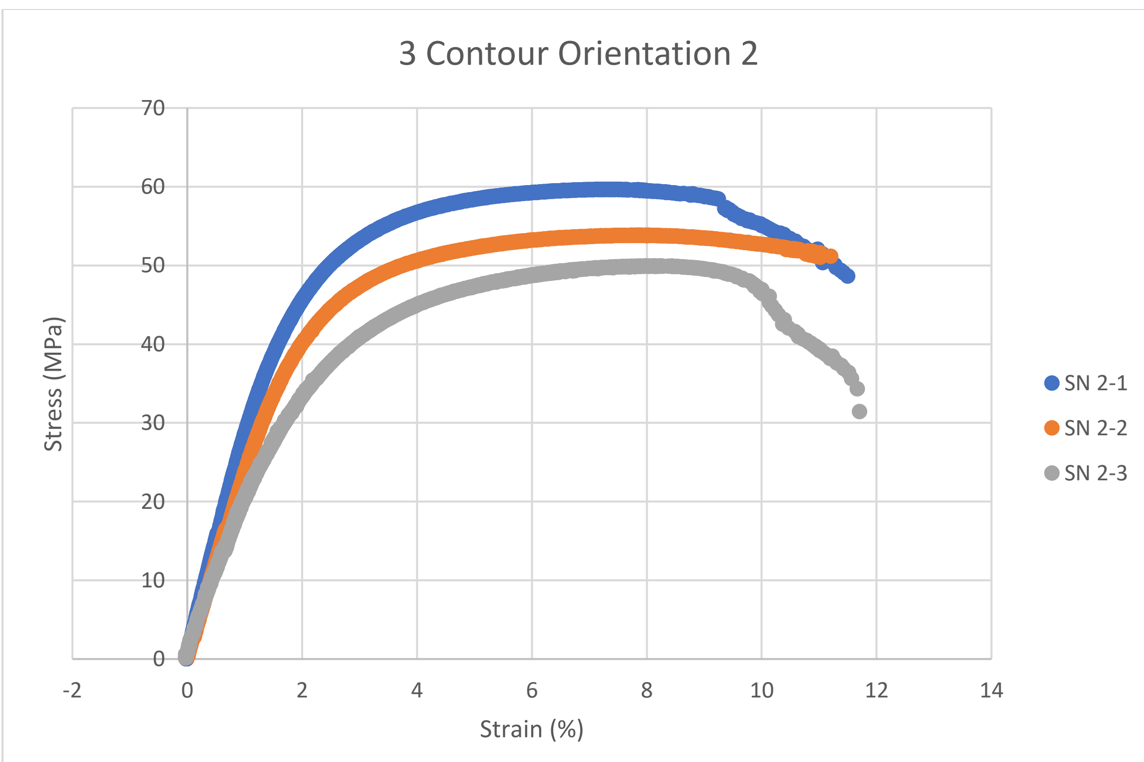

Figure 20: 3 Contour Orientation 2 Stress-Strain Curve

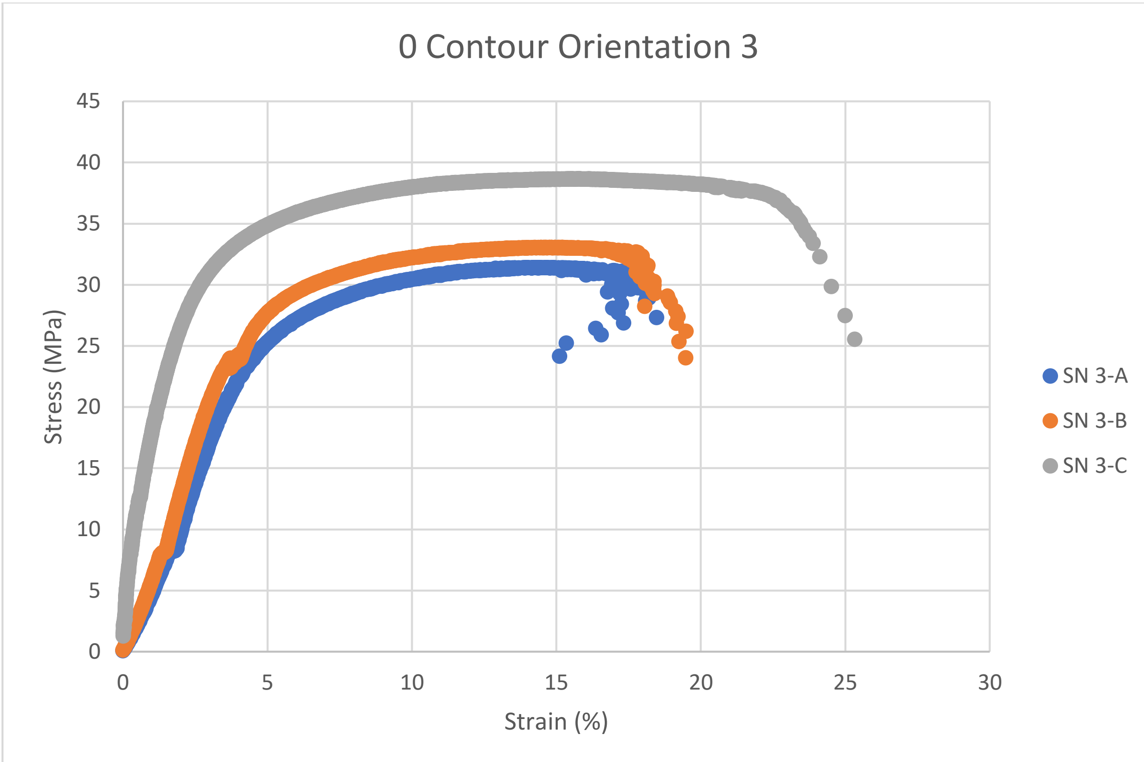

Figure 21: 0 Contour Orientation 3 Stress-Strain Curve

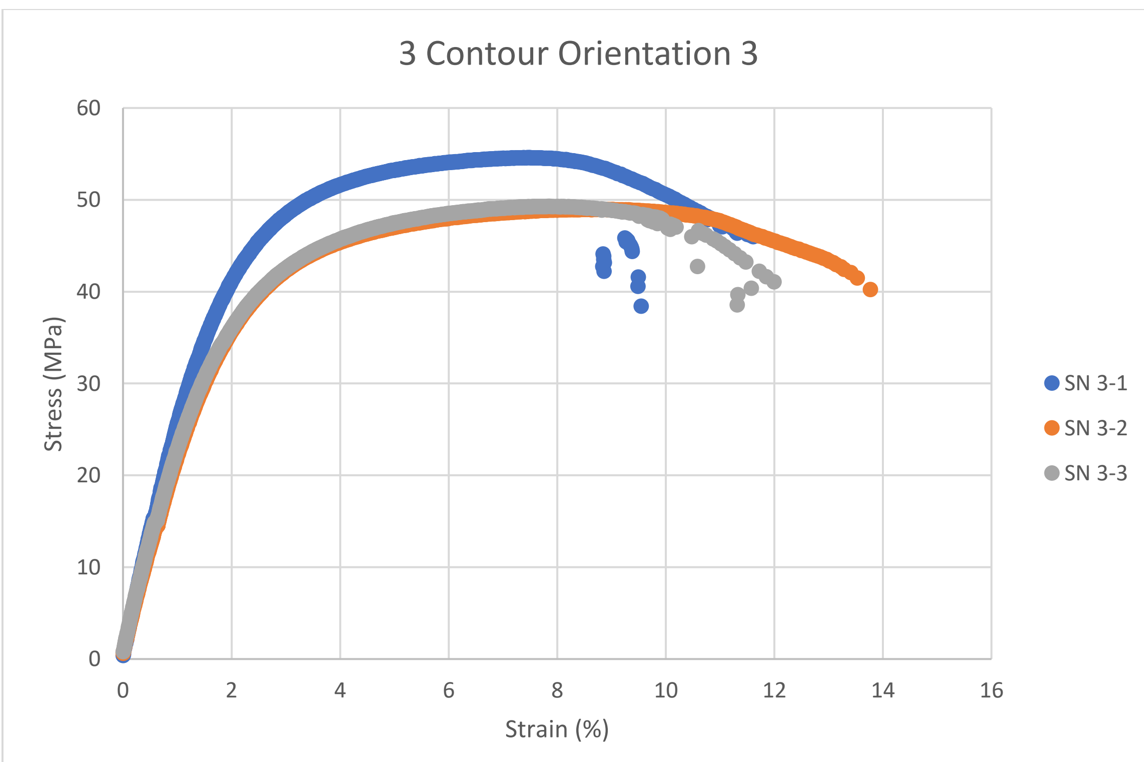

Figure 22: 3 Contour Orientation 3 Stress-Strain Curve

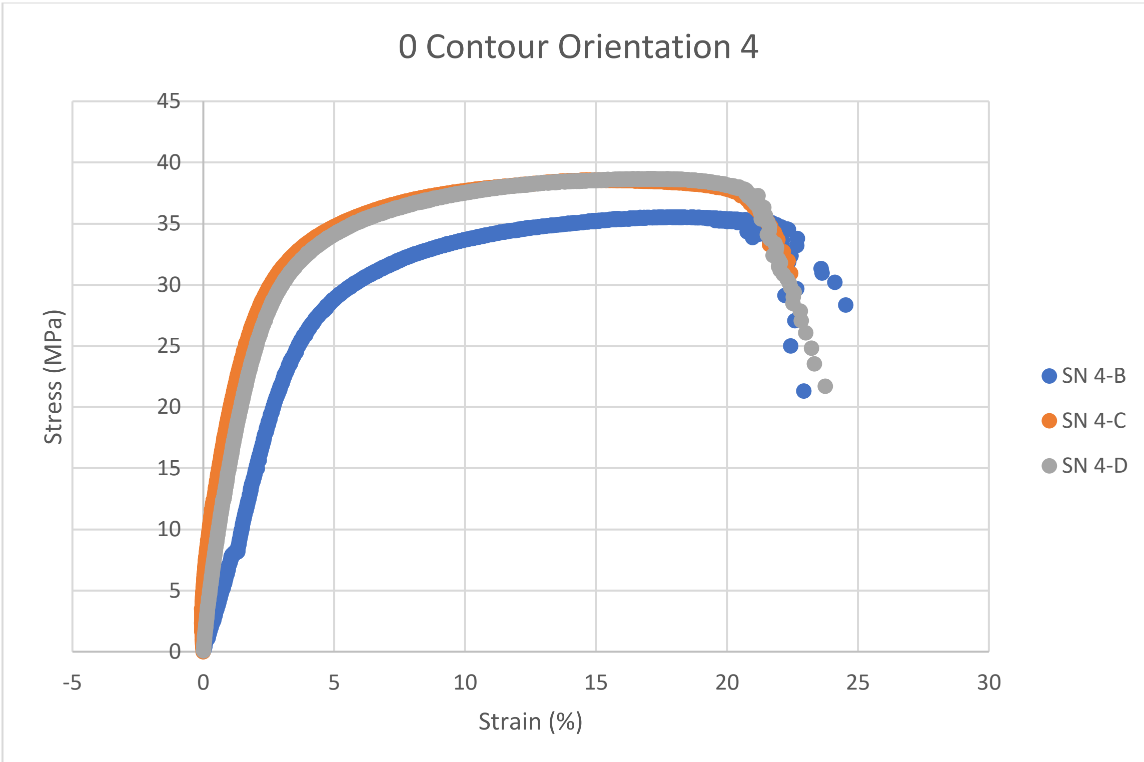

Figure 23: 0 Contour Orientation 4 Stress-Strain Curve

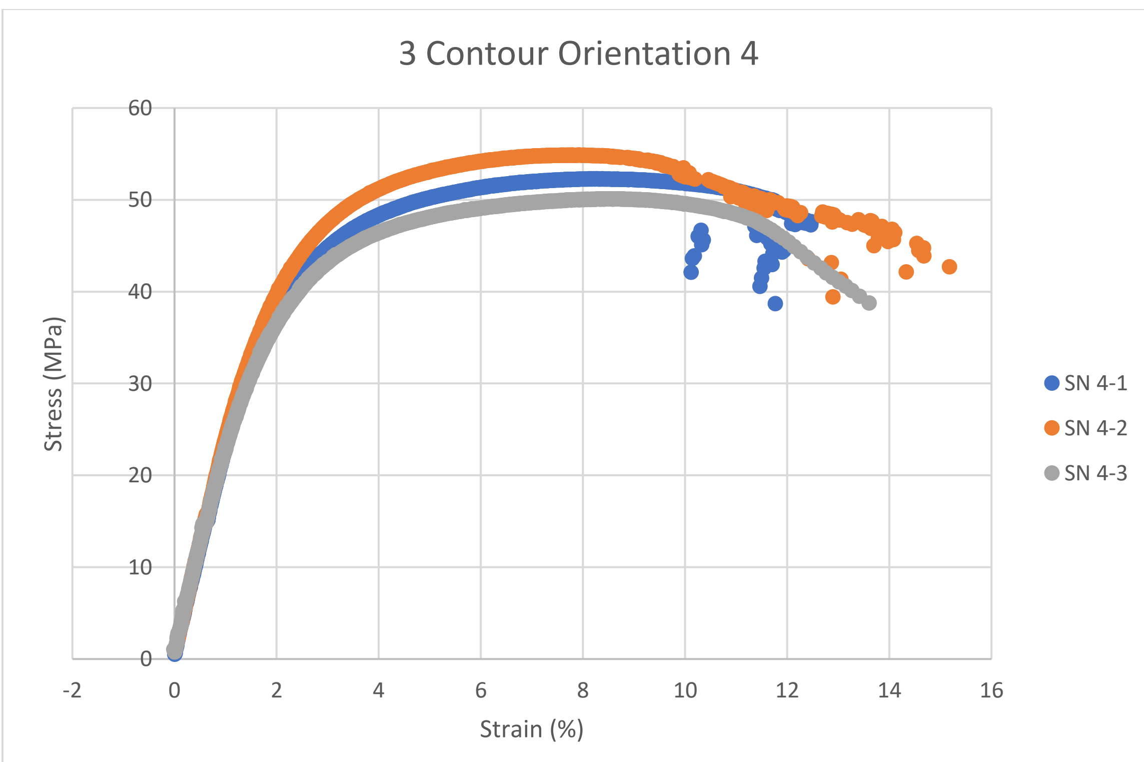

Figure 24: 3 Contour Orientation 4 Stress-Strain Curve

Overall, data set two provides two sets of results that can be analyzed. Firstly, the inconsistencies visible in the stress strain curves can be analyzed for deficiencies in the testing method and data collection method. Secondly, with what should be an accurate stress-strain curve, the modulus of elasticity for each coupon can be calculated.

The stress-strain curves from the DIC data in the above figures are largely inconsistent, with only the zero contour orientation 2 showing a reasonable level of consistency. This inconsistency carries through when the modulus of elasticity is calculated for each of these sample coupons. To calculate the modulus for each coupon, the slope of each graph was determined from the linear (or most linear) section (stress over strain, generally around the 20-30 MPa range). This gave results found in Table 6 below, which lists the modulus for each coupon as they are labeled on the curves above. As can be seen from this data, results were inconsistent to the same extent that the stress strain curves were inconsistent.

Modulus of Elasticity (MPa)							
	3 Contour			0 Contour			
Coupon Label	**1**	**2**	**3**	**A**	**B**	**C**	**D**
Orientation 1	20.317	18.585	34.758		6.938	18.047	21.138
Orientation 2	29.154	23.513	21.463	25.859	25.364	28.421	30.073
Orientation 3	25.636	21.424	22.043	5.736	6.859	16.941	
Orientation 4	22.747	23.924	22.519		7.495	19.478	13.996

Table 6:Modulus of Elasticity (MPa) Calculated From Stress-Strain Data

Given how much the DIC data varied, it is hard to draw conclusions with any degree of confidence; however, the 3 contour samples showed a higher modulus of elasticity than their zero-contour counterparts, except for orientation 2. This tracks with the data from dataset one and accepted knowledge about Material Extrusion parts. The contours are able to carry load, and the material has its best properties when the load is parallel to the print direction. It is also reasonable that orientation 2 didn't follow this trend, as the contours and infill for this orientation are in the direction of the load, and therefore, the lack of contours does not adversely affect the ability to handle the load.

While the exact cause of the inconsistencies cannot be determined without attempting to recreate the inconsistent data, there are a few likely candidates. The first likely cause of inconsistencies is the method by which the DIC software and hardware perform its image capture and recognition, as discussed above in the equipment section. While viewing the coupon through the software, the system will estimate if there are enough unique features on the coupon to use for correlation. This value does not account for coupon elongation during pull testing, and several coupons tested yielded unusable data near the fracture point. Some of these captured videos were postprocessed to increase contrast and approximate strain, but some could not be used at all. This shows how delicate the system is for data collection, and this likely contributed some of the inconsistencies to the data in this data set.

The other likely area for the inconsistencies in this data set comes from the printing process itself. Additive manufacturing is generally less consistent than subtractive manufacturing. During the manufacturing process of the coupons, some failed due to under-extrusion and poor bed adhesion. It is likely that some of the coupons that were manufactured successfully still had these issues, but not to the extent that they failed. Under-extrusion in the inner layers, which cannot be seen, would particularly introduce significant inconsistencies into this data.

3.3 Fracture Results

In addition to the tensile bars above, notched bars were pull tested to guarantee failure in a known and comparable location across the various infill directions and contour amounts. A set of samples from the 0 contour group can be found in Figure 25 and a set of samples from the 3 contour group can be found in Figure 26 below.

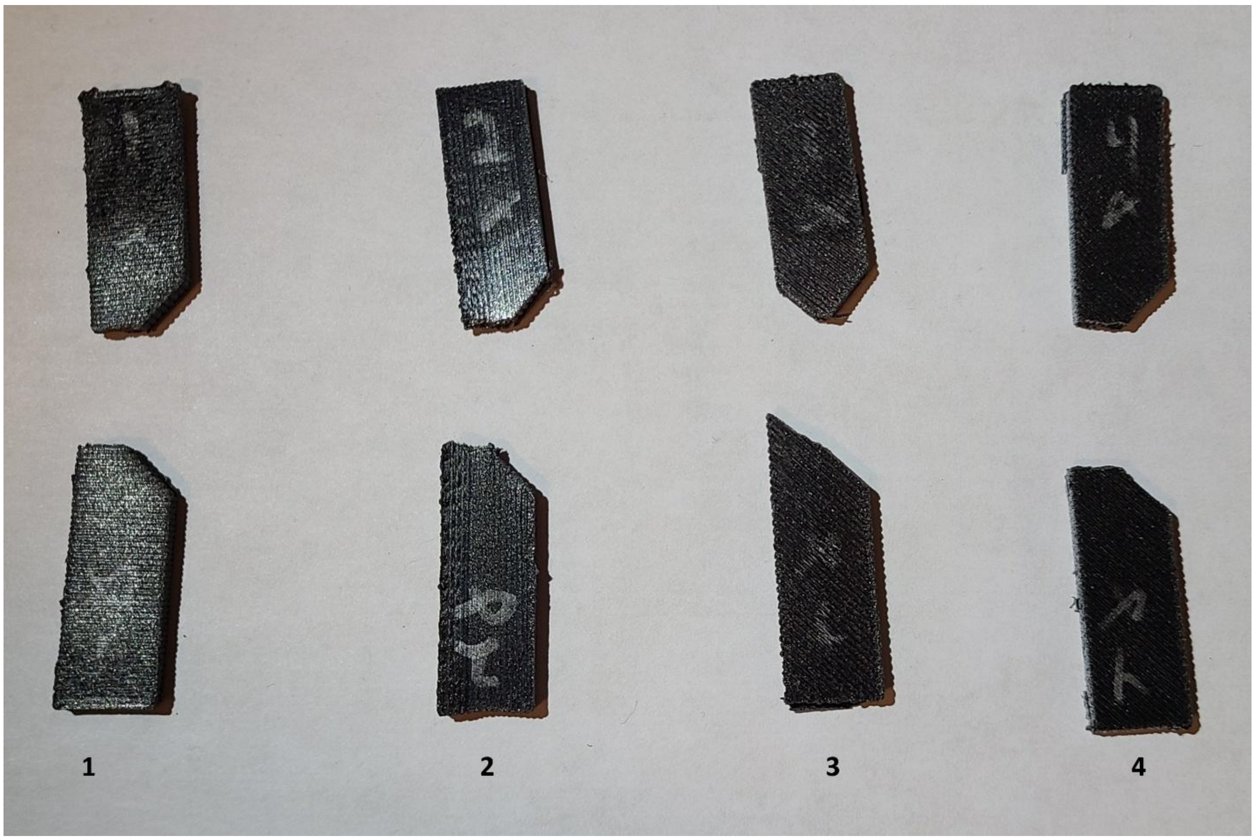

Figure 25: 0 Contour Notched Bars

Based on Figure 25, both orientation 1 (0° infill) and orientation 3 (45° infill) fractured parallel to the infill direction (the weakest direction), creating clean splits starting at the notch. Orientation 2 (90° infill) fractured flat across from the notch, which is perpendicular to the infill orientation, as there was no weak direction perpendicular to the load for the fracture to run down. Instead, when the infill line closest to the notch fractures, the load is transferred directly to the next infill strand in line and they fail in a line going across. Similarly, the orientation 4 (alternating 45° and 135° infill) samples fractured across cleanly, due to the weak direction alternating layer by layer.

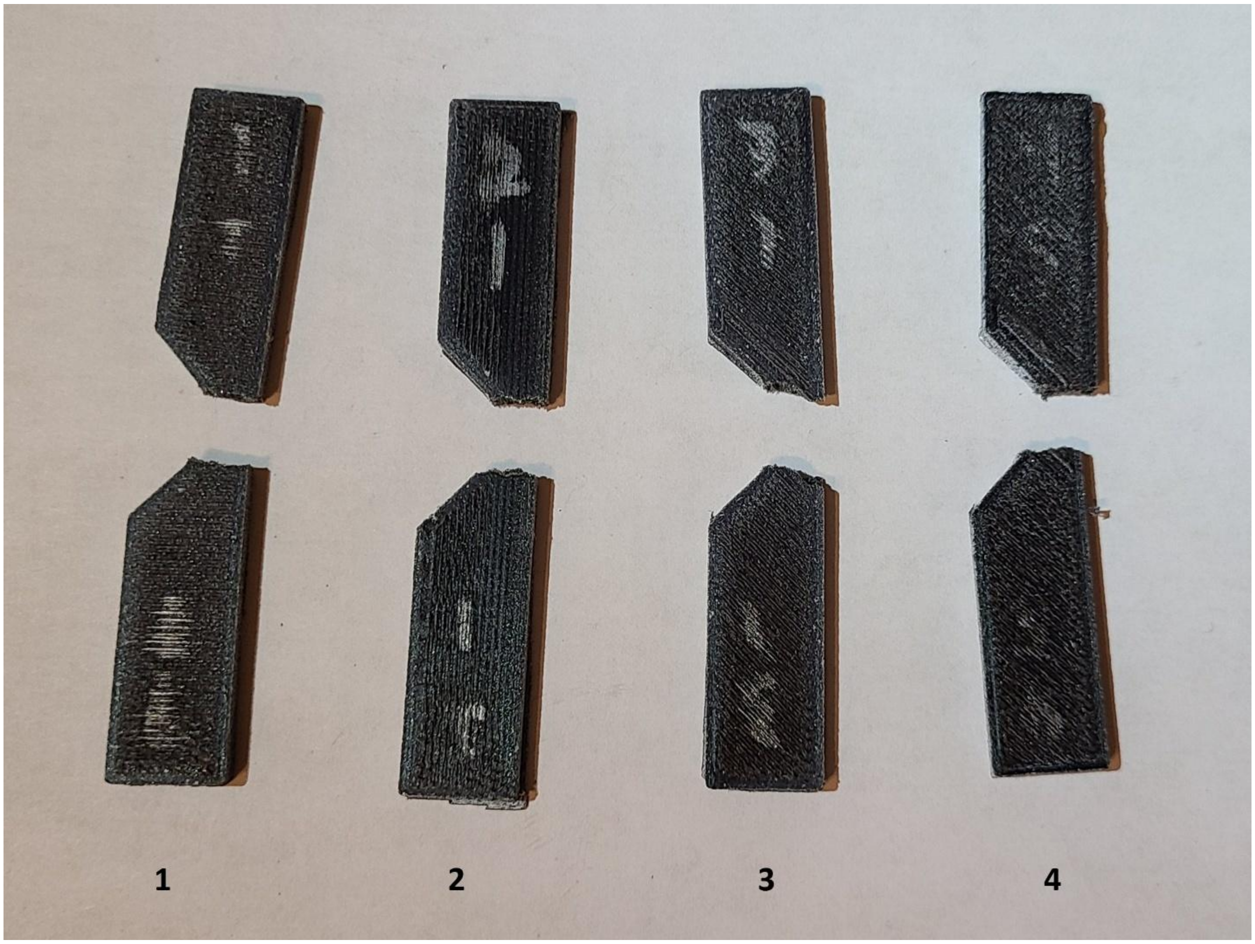

Figure 26: 3 Contour Notched Bars

Figure 26 shows the 3-contour version of Figure 25. Orientations 1, 2 and 4 (0°, 90° and alternating 45° and 135° infills, respectively) all appear similar to their 0 contour counterparts for similar reasons to above. Orientation 3 (45° infill) does not show the sharp 45° fracture that is reflected in the 0-contour version. This is due to the coupon having contours that can handle the load at the fracture location and mitigate some of the fracture direction. It can be seen in Figure 27 that after the contours, the fracture began to follow the infill direction but was halted by the contours on the non-notched side. A careful examination can see on the right side of the lower piece next to the contours that the fracture was not even across the layers.

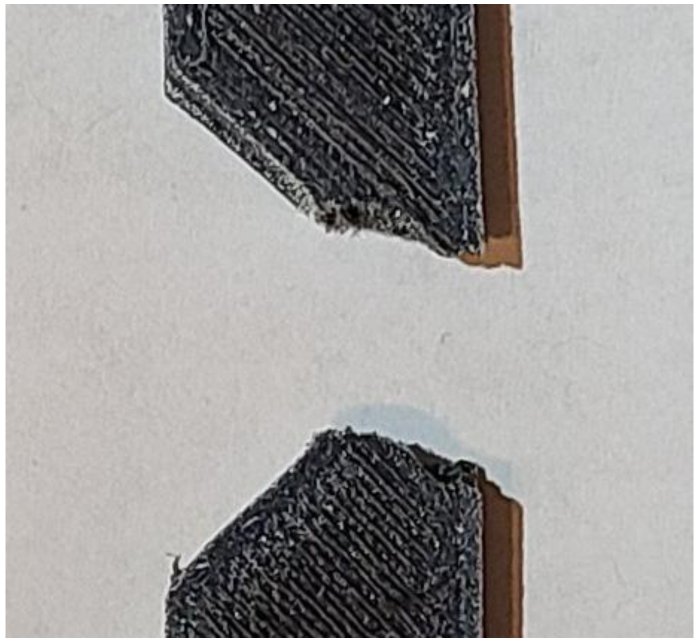

Figure 27: 3 Contour Orientation 3 Fracture Surface

Chapter 4: Conclusions and Future Research

4.1 Conclusions

Additive manufacturing technology is still maturing, with new features and improved consistency coming every year to the industrial scale equipment. As the industrial scale processes mature, more of the new features from previous years are scaled down to hobby level equipment, resulting in more budget friendly devices capable of consistency and manufacture with engineering materials. This is a good thing, because the research in this paper suffered from a lack of consistent printing using a machine (Creality Ender 3 S1 Pro) that was technically acceptable per manufacturing specs for the nylon 6 carbon fiber reinforced filament used, but only at the extreme margins of the machine specifications. While a filament drier and a print enclosure were used in addition to the printer, that was only enough to get marginal consistency from manufactured coupons. A heated build chamber would be necessary to ensure reasonable consistency across printed samples, and adding a heater to the chamber is not a minor modification to make to a prebuilt printer. Hobby-level printer manufacturers, such as BambuLabs, are now even producing machines designed with a heated chamber, something which was not available at the beginning of this research.

Looking at the results achieved through the testing in this paper, the generally touted design considerations were validated. Inclusion of contours to layers were shown to increase the maximum load, maximum stress and modulus of coupons across all infill directions. Similarly, it was seen that infill direction, even with contours, can increase the maximum load, stress and modulus that a part sees. This shows that for designs with known load cases, an engineer can vary the number of contours on a per layer basis to adjust time and strength of a load, and can even vary the direction of the infill to strengthen specific layers against specific directions of loading. Looking at the fracture surface of the notched bars also showed that alternating infill directions will force a fracture to run perpendicular to the load, rather than creating an easy path for it to propagate.

Another conclusion that can be drawn from the inconsistent data in this paper is the necessity to validate material and process parameters using local equipment, rather than simply accepting the data provided by the material manufacturer. Quoted tensile strength for this material was listed by the material manufacturer at 100 MPa; however, through testing, even the most ideal of the tested parameter sets, contours, and infill in the direction of loading, still saw only about half the quoted tensile strength. That is enough of a difference to eat a majority of the factor of safety designed into many components. Rigorous local testing is therefore a necessity to ensure that parts manufactured through Material Extrusion, such as those featured in this paper, do not fail prematurely and cause damage and set back the adoption of Additive Manufacturing in industries that would benefit from the advantages it offers.

4.2 Future Research

For continuation of this research, there are many paths that could be taken. The first option that should be explored is the inclusion of a traditional strain gauge on any coupon being tested. This will allow for confirmation of the DIC data after collection and comparison of the stress-strain curves from a traditional method compared to the DIC method. This itself would be a good topic regardless of if the coupons were additively manufactured or not, as confirming best practices for getting accurate DIC data would be useful.

Going further, repeating this research with a larger sample size would allow for better trending of the data, and an ability to remove outliers consistently from the results, which will allow for much more complete conclusions in addition to quantifying outliers and causes of failure. Adding additional infill types to the testing would also be a worthwhile path of study. This study primarily discussed designs in which loads would be monodirectional. This is rarely the practice case. Inclusion of 0° and 90° alternating infill (parallel and perpendicular to the load direction) would be useful to assess the drop-off in properties and how it compares to the alternating 45° and 135° samples. Another interesting infill type to explore would be 30° increments (0°, 30°, 60°, and 90°, repeating), which would yield more consistent properties in a part where loads could come from any direction. The last coupon style that would be interesting to see would be coupons that do not lie flat on the bed. A coupon printed with layers perpendicular to the direction of load (the coupon standing vertically on the bed of the printer) would be the most telling of layer weaknesses, if they could be manufactured consistently. Beyond that, a set of coupons printed on an angle so the layer lines are not parallel to any face of the coupon could produce interesting results, if an adequate support material can be used.

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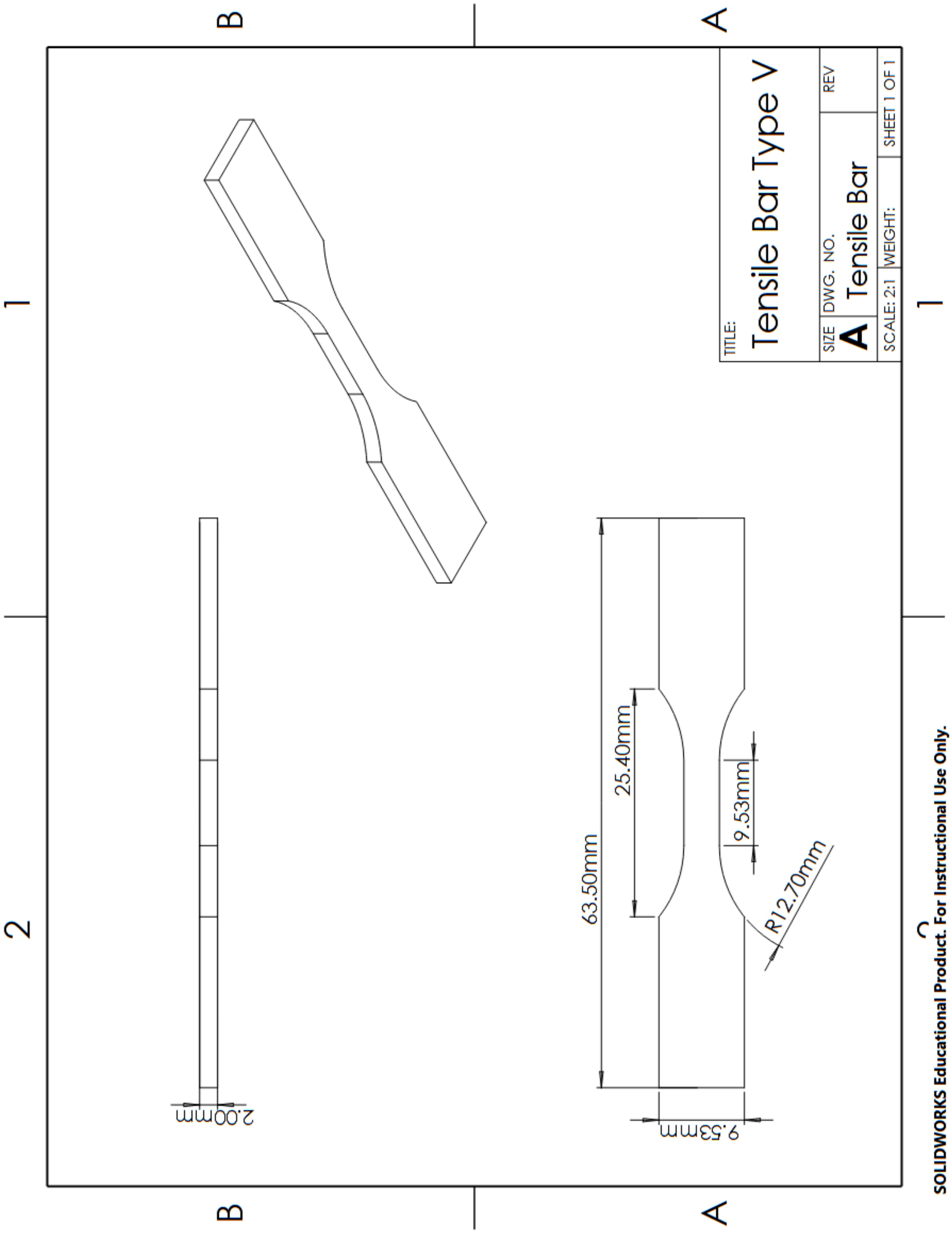
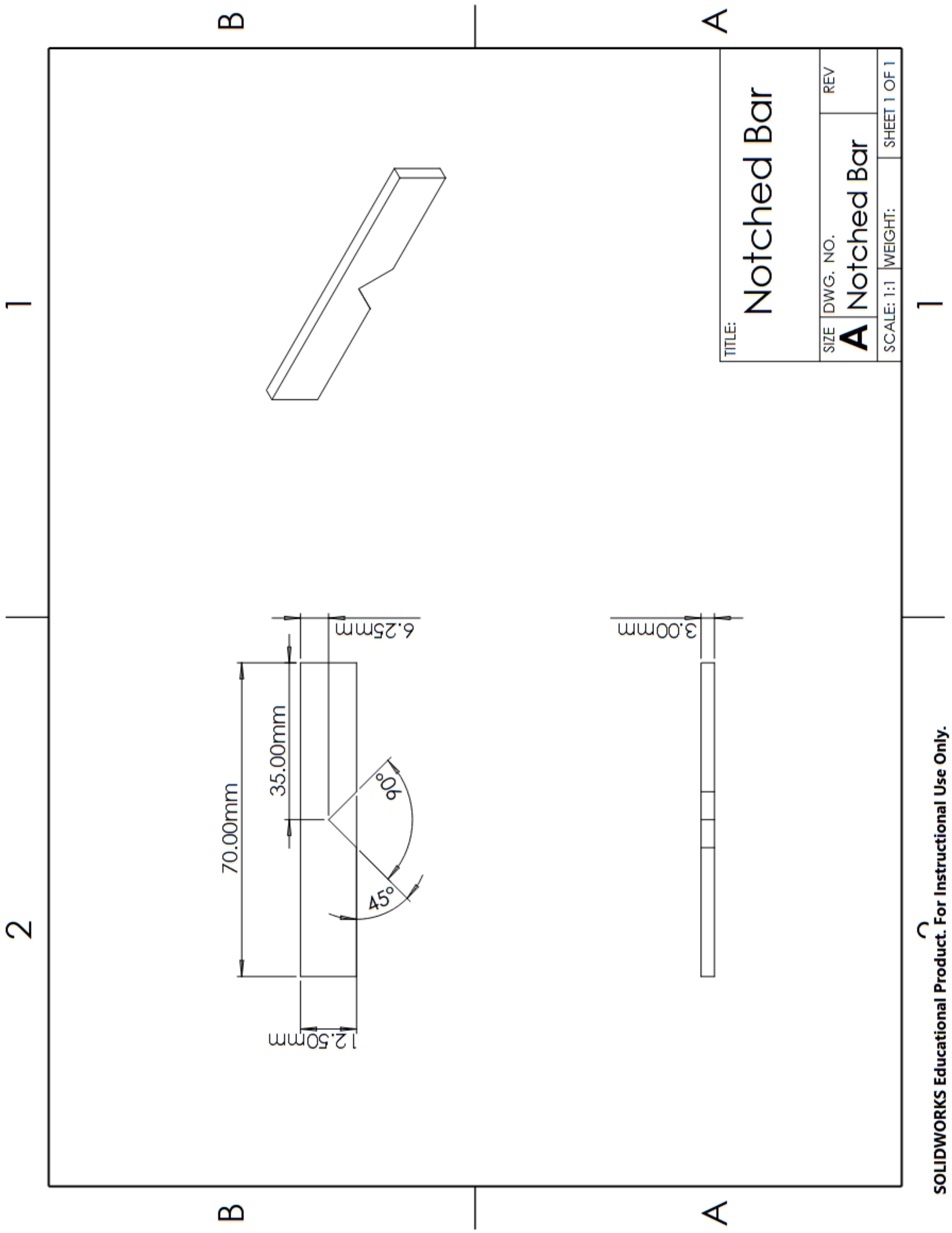
Appendix A: Tensile Bar Drawing



Appendix B: Notched Bar Drawing



Appendix C: Selected Print Parameters

Coupon Lot	Layer Height (mm)	Infill Direction	Print Speed (mm/s)	Print Head Temp (Celsius)
Tensile Bar 1	0.2	0	35	265
Tensile Bar 2	0.2	90	35	265
Tensile Bar 3	0.2	45	35	265
Tensile Bar 4	0.2	45/135	35	265
Notched Bar 1	0.2	0	35	265
Notched Bar 2	0.2	90	35	265
Notched Bar 3	0.2	45	35	265
Notched Bar 4	0.2	45/135	35	265

Table 7: Selected Parameters Part 1

Coupon Lot	Build Plate Temperature (Celsius)	Infill Density (%)	Top/Bottom Infill Direction
Tensile Bar 1	65	100	0
Tensile Bar 2	65	100	0
Tensile Bar 3	65	100	0
Tensile Bar 4	65	100	0
Notched Bar 1	65	100	0
Notched Bar 2	65	100	0
Notched Bar 3	65	100	0
Notched Bar 4	65	100	0

Table 8: Selected Parameters Part 2