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Paper

3D PRINTING APPLICATIONS IN WATERJET NOZZLE FABRICATION

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ABSTRACT

Conventional manufacturing methods have historically limited the ability to economically fabricate a wide variety of potential nozzle designs for use in commercial and research applications. Nozzles manufactured using subtractive methods (conventional machine tools) are often severely constrained in terms of possible internal geometries, orifice placement, and the configuration of flow paths, and routinely experience poor performance and inefficiencies associated with tool marks and abrupt changes in the nozzles internal annulus. The recent development of reliable and affordable additive manufacturing methods is providing an opportunity to overcome these challenges. Additive manufacturing, commonly referred to as 3D printing, builds solid parts through sequential layering. As such, it is now possible to produce nozzles and other intricate components with almost any internal geometry using materials ranging from many types of plastics to steel and titanium. This paper presents the current state of this technology and its novel applicability in waterjet research and component manufacturing.

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1.0 INTRODUCTION

Traditionally, the production of one piece metal parts has been dominated by subtractive processes, forging, and casting. Subtractive processes, such as conventional milling or turning a part on a lathe, remove material to produce the finished part. Forging uses dynamic impacts to force hot metal into specific geometries. Castings are made by pouring molten metal into a mold where it hardens. Due to geometry limitations and surface roughness, subtractive manufacturing is the dominant process used in producing waterjet nozzles. However, subtractive manufacturing still has significant disadvantages due to the constraints that it places on nozzle design.

There are three major drawbacks with subtractive processes. First, curves are difficult at best. A simple two dimensional curve (such as a filleted corner in a pocket) may require a tool change. Compound curves are far worse and may require a specialized tool and a state of the art multi-axis CNC mill if they are even possible. Second, tool geometry severely restricts the internal geometry of machined parts. It is not possible to position a tool inside the part to make many of the features that would be easy to cut on the outside of a part. Third, machining processes often leave tool marks and may have abrupt transitions where tool changes or sequential drilling has occurred.

Additive manufacturing drastically mitigates these drawbacks. By building the part in layers, a 3D printer has unrestricted access to the inside of the part. If a 3D printer can print a feature, it can print it almost anywhere. While there are still some design rules for additive manufacturing, 3D printers are capable of producing almost any surface geometry.

Despite these advantages, additive manufacturing still has significant drawbacks. 3D printers tend to produce rougher surfaces than subtractive processes. Furthermore, the deposition of material often leads to undesirable material properties. Until recently, the severity of these drawbacks was sufficient to preclude the use of additive manufacturing in many precision applications.

Figure 1: Fully functional 3D printed 1911 by Solid Concepts (Stratasys).

However, additive manufacturing technology is advancing rapidly. As of 2015, the capabilities of additive manufacturing have reached the point where 3D printed metal parts can often be used as an alternative of machined parts. In 2013, NASA tested a 3D printed injector in a rocket test that produced 20.000 pounds of force (NASA). During the same year, Solid Concepts 3D printed a fully functional 1911 pistol in .45ACP (Stratasys). The Solid Concepts 1911 has since successfully fired over a thousand rounds (Stratasys). As these milestones indicate, additive manufacturing is now a viable option for high stress applications.

2.0 LIMITS OF SUBTRACTIVE MANUFACTURING

Subtractive manufacturing is constrained by tool geometry, tool access, and the CNC mill's degrees of freedom. When a part's geometry is a good match for the tool and the mill has the appropriate degrees of freedom, a mill or lathe can be very effective. However, complicated parts may run up against one or more of these constraints. These constraints then force the designer to adopt a less ideal geometry. In waterjet applications, these geometry compromises are often found in the interior geometry of nozzles. Nozzle manufacturing is of particular interest because it runs up against all three constraints.

Tool geometry determines the shape of a cut for a given tool path. For example, an end mill is going to make a cut that has a flat bottom and straight sides. This tool geometry is useful for cutting slots with straight sides in a part. However, if a fillet is desired on the bottom of the pocket, the tool will need to be swapped for another tool with the appropriate end geometry. Due to the widespread availability of tools designed for common and simple geometries, tool geometry is not an issue for many jobs. Tool geometry becomes a limiting factor for designs with more exotic geometries.

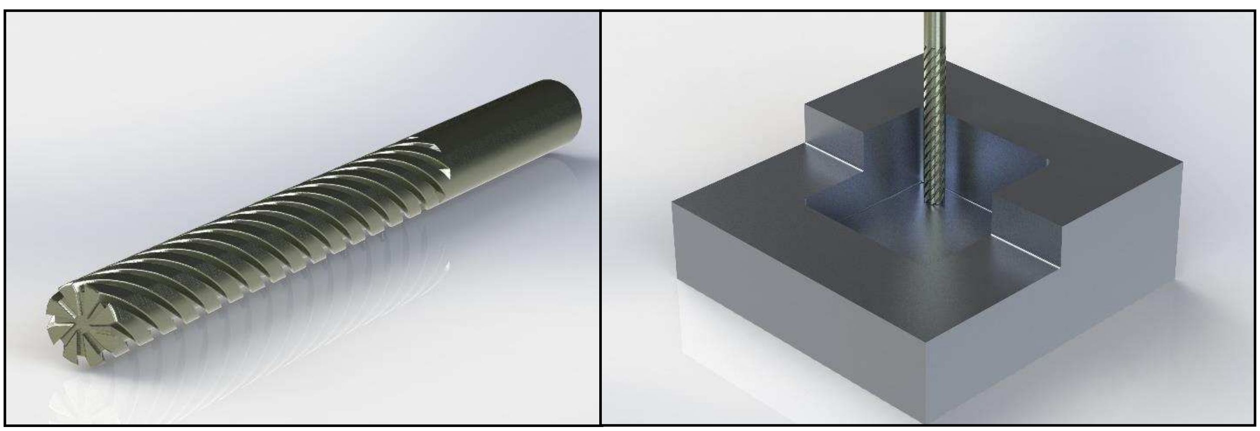

Figure 2: End Mill and its use to cut a pocket in an aluminum block. Note that the end mill produces a flat bottomed pocket with straight sides and filleted corners.

A machine's degrees of freedom determine its possible toolpaths. For CNC milling machines, three degrees of freedom is the minimum. A milling machine with three degrees of freedom can move its tool to any point in its workspace. However, the alignment of the tool's axis cannot be changed. With three degrees of freedom, a mill can easily cut straight sided features like the pocket shown in Figure 2. The addition of two more degrees of freedom would allow a toolpath that could chamfer the top edge of the pocket. It is important to note that additional degrees of freedom do not fully translate into freedom from geometric constraints. While it is easy to add a toolpath for a chamfer or a fillet, a fillet with a variable radius is much more difficult. At 5 degrees of freedom, subtractive manufacturing can push the technology further at the cost of increased complexity and more complicated toolpaths.

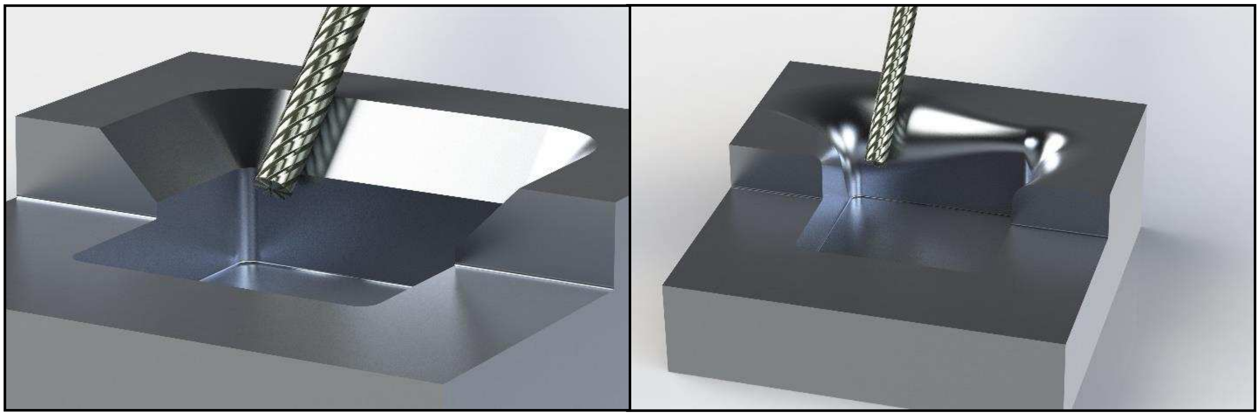

Figure 3: A chamfer, which is possible with a 5 axis CNC mill and an arbitrary variable radius fillet which cannot be exactly machined (though it could be approximated with enough tool passes).

Access to the surface to be machined is critical to subtractive machining. This is what makes internal geometries more difficult. As access is reduced, the possible tool paths and tool geometries are reduced. Operations that would be easy with stock tooling on the surface become difficult or impossible in internal cavities. Complicated surfaces and curved passages are impossible for all practical purposes.

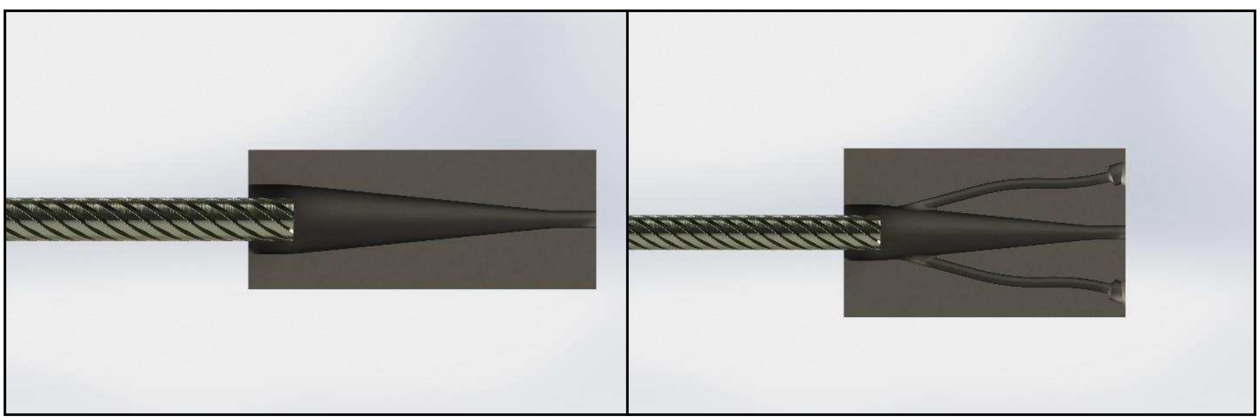

Figure 4: The pictured tool cannot produce the internal chamfer, although specialized tools could stull produce the geometry on the left. The curved passageways in the right model cannot realistically be produced through subtractive manufacturing.

The access problem compounds subtractive manufacturing's issues with surface finish, tool marks, and abrupt transitions. It is much harder to mitigate tool marks or polish a surface in a difficult to access passageway. The confined space also means that the tool geometry is the main parameter that can be varied. The only way to add some features with stock tooling is through sequential drilling. This means tool changes and increases the likelihood of abrupt transitions between operations. High quality custom tooling can mitigate the abrupt transitions, but is often cost prohibitive.

All three of these constraints come into play in waterjet nozzle design. The geometry of readily available tooling constrains the shape of cuts that can be made. The confined geometry and nature of the available tooling restrict the degrees of freedom and possible tool paths. Effectively, these constraints limit the tooling in nozzle construction to pre 5 axis CNC machining technology. Tool movement is limited to a single axis. Tool geometry is usually limited to cylindrical and conical bits. The end result is that nozzles are often lacking basic internal features like fillets that could improve efficiency.

Unfortunately, the situation in subtractive manufacturing is not likely to improve significantly for waterjet nozzle construction. Subtractive manufacturing is a mature technology, where most of the recent improvements have been in automation and control, not the fundamental process. The constraints involved in machining waterjet nozzles have effectively negated most of the recent technological advances. The ability to quickly design a part in a CAD program like SolidWorks, program the toolpaths in a program like Mastercam, and then export the G-code (machine movement commands) to a 5 axis CNC mill, does not overcome the shortcomings of subtractive manufacturing.

3.0 ADDITIVE MANUFACTURING TECHNOLOGY

In 3D printing, the part is built by adding material to form the desired geometry. The vast majority of additive processes build parts in two dimensional layers. These layers are generated from the CAD file and are analogous to contour lines on a map. The print will start at the bottom layer and add material within the contour lines. There are two general paradigms of material deposition. In the first, material is only added where it is needed and all of the material is bonded to the part. In the second, the material covers the entire layer but is only bonded within the contour of the part.

The 3D printing process starts with a CAD model in a program like SolidWorks. The file is then sent to a program called a slicer, which is often integrated with the 3D printer's control software. The slicer cuts the CAD model into layers and generates the tool paths required to build the layers. These paths are typically exported as G-code, which contains the low level commands that drive the printer's components. Once the slicer has generated the tool paths for the print, the printer control software will home the system and then begin running the print.

It is important to note that the capability of going straight from CAD to a plastic part has a significant impact on prototyping. One of the authors (Charrier) uses a consumer grade 3D printer as part of a mechanical engineering consulting business. The fast turnaround time afforded by the 3D printer enables the business to implement client feedback and test several iterations of the design within a day of receiving the feedback. This has significantly reduced lead times during the design phase and lead to a more refined product.

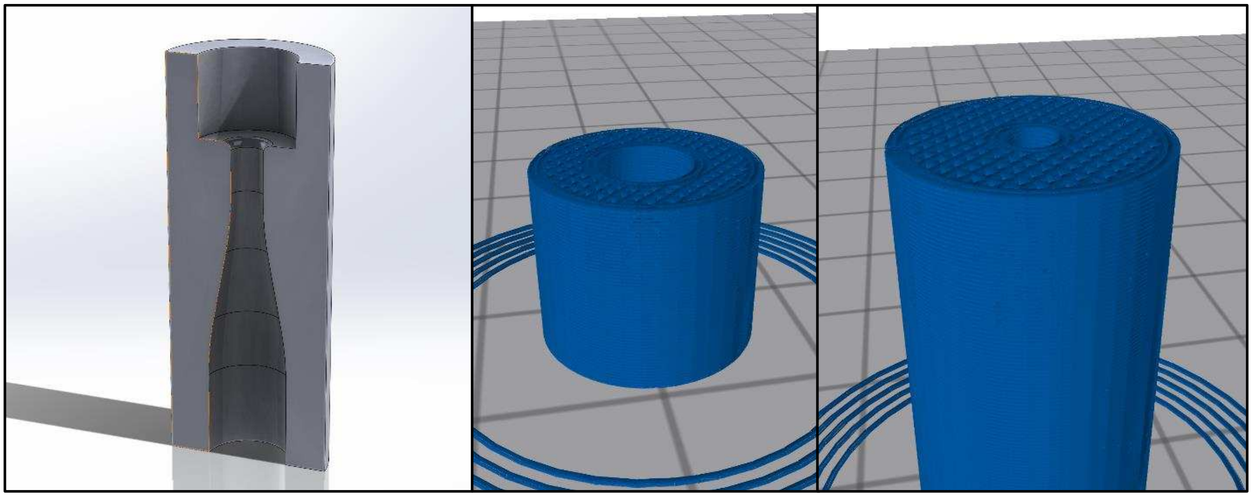

Figure 5: 3D printing workflow. A section view of the model in SolidWorks is shown on the left and middle and right images show different layers of the part. Note that the path the extruder will follow is indicated by the lines in the surface of the part. This part should take approximately 40 minutes to print with an extruder speed of 60mm/s.

Breaking 3D printed parts into discrete layers has two significant impacts on part geometry. First, this layered structure is what allows 3D printed parts to approximate almost any geometry. While the height of a layer is fixed, the path is variable. This allows the printer to follow the edge of the part and produce the approximated geometry. Second, the layers guarantee that there will be surface roughness. The magnitude of the roughness is dependent on the thickness of the layers, the accuracy of printer's movements, the material, the temperature, and other factors. Many printers are capable of varying the layer height depending on the requirements of the job.

Layer thicknesses vary greatly depending on the technology employed. Consumer grade 3D printers, such as Robo 3D's R1, are typically capable of printing 0.1mm to 0.3mm layers. Higher end professional models are capable of far higher resolution. For example, Stratasys Direct is advertising layer thicknesses as low as 40-60 microns for their direct metal laser sintering service (Stratasys). Stratasys Polyjet systems are capable of producing layers as fine as 16 microns (Stratasys). Protolabs is currently offering direct metal laser sintering layer thicknesses of 20 microns (Protolabs). All of these are currently commercially available products or services.

It is important to note that 3D printing can have a significant impact on the material properties of a part. First, building a part in layers means that there will be numerous small joints throughout the part. The material properties of these joints are often different from the properties of the rest of the part or a conventionally manufactured part of the same material. Typically, the joint is weaker than the surrounding material. This tends to be an issue with consumer grade plastic 3D printers, where part failure as a consequence of delamination is common.

Second, many 3D printing processes involve heating a region of the part. This means uneven cooling of the part is likely. Parts approaching the size of the build area on consumer grade 3D printers often experience significant warping of the extremities. Even if visible warping does not occur, uneven cooling can result in residual stresses in the part.

Third, 3D printing – especially with consumer grade printers – can result in uneven material deposition rates. If the filament (feedstock) is too small or extruded too slowly, an insufficient volume of plastic is extruded and can lead to void spaces inside a part. These voids cause stress concentrations and can cause the part to be susceptible to fluid penetration. If the filament is too thick or is extruded to fast it can lead to too much filament being deposited. Too much filament will cause the part to expand in that region. This problem primarily exists in the lower end plastic printers and is a function of incorrect settings or varying feedstock.

Finally, 3D printing may result in varying and potentially undesirable grain structures in a material. In processes where the material is melted locally, most material will be melted once and go through several heating and cooling cycles as the laser or extruder moves beside and above a point. The cooling rate is not fully controlled and these cycles can change the material properties. With some materials, a metal part can be annealed to mitigate this, but this is not true of all materials.

The problems with 3D printing processes can typically be mitigated by selecting the right material and process. Quick proof of concept prototypes can be run on almost any 3D printer. For example, the Colorado School of Mines uses consumer grade printers to produce ABS parts. Far higher quality printers and printing services are available from companies like Stratasys Direct. These printers can mitigate most process related problems. The key is to match the material and process to the application.

4.1 Additive Manufacturing Methods

The recent explosion in the availability of consumer grade 3D printers was caused by the expiration of U.S. patent US5121329A in 2009 (Crump). This was the core patent for fused deposition modeling (FDM) and lead to the founding of Stratasys (Crump, Brewster). Once the patent expired, low cost consumer oriented companies, like MakerBot, flooded the FDM market and drove prices down. Thanks to these companies, FDM printers make up the vast majority of consumer grade 3D printers on the market. It is now possible to buy a complete FDM 3D printer for approximately $800. The printer used by Charrier is a slightly modified Robo 3D R1, which retails for the same amount.

FDM printers work by extruding a bead of molten plastic filament. The extruder, which has 3 degrees of freedom, fills in the part's contour in each layer. When a layer is complete, the extruder moves up to the next layer and builds that contour on top of the preceding layer. Where there is an overhang, the printer will build a support structure to support the part.

A second wave of consumer grade 3D printers has emerged using stereolithography. The core patents on stereolithography were developed by 3D Systems during the 1980s and early 1990s (Brewster, Hull). Stereolithography works by using light to selectively cure resin in a tank. This allows intricate 3D shapes to be formed within the tank. Formlabs is playing a role analogous to Makerbot in bringing stereolithography to consumers.

Polyjet printing was developed by an Israeli company, Objet Geometries, around 2000 and is still covered by U.S. patents (Gothait). The Polyjet process works by spraying resin droplets on the model surface and immediately curing the resin with a laser or other light source. As necessary, a polyjet printer will use support material for overhangs. Objet was acquired by Stratasys in 2012 (Bloomberg). Stratasys Polyjet systems are producing layers as fine as 16 microns (Stratasys).

Selective laser sintering is used to 3D print metal and plastic parts. The technology was developed by DTM, which was then acquired by 3D Systems (Krassenstein, Deckard). The key patent on laser sintering expired in 2014 (Deckard). Selective laser sintering works by spreading a thin layer of metal powder over the work area and then sintering the areas within the part geometry with a laser. When that is complete, another layer of powder is spread across the build area and the cycle is repeated.

Laser metal deposition is a versatile technology that can be used to build, repair, or coat parts. The process works by melting the surface of a material and then blowing metal powder into the melt pool (RPM Innovations Inc.). This allows laser metal deposition machines work without any support material and makes it far more useful for maintenance and surfacing operations. According to LPW, which provides powder for laser metal deposition, the process may be called Laser Metal Deposition, Direct Metal Deposition. Direct Laser Deposition, Laser Engineered Net Shaping, Laser Cladding, Laser Deposition Welding, and Powder Fusion Welding (LPW Technology).

Electron beam additive manufacturing (EBAM) was patented in 2001 by Arcam Ab (Andersson). EBAM is similar laser metal deposition. Metal powder is dispensed onto the surface and then the powder is fused to by the electron beam. EBAM machines are capable of working with a wide variety of metals and have large work areas. Sciaky's EBAM machine can build parts up to 5.8m x 1.2m x 1.2m and can work with titanium, steel, Inconel, tantalum, tungsten, niobium and other metals (Sciaky).

Despite all of its advantages in geometry, 3D printing is still behind subtractive manufacturing in terms of surface finish and quality. However, this shortcoming can be overcome by using a hybrid process. It is now possible to combine 3D printing with a milling machine. DMG Mori has developed a combination laser deposition welding and 5 axis CNC machine, the LASERTEC 65 3D. This system can automatically switch between laser and milling operation and achieve machining quality surface over most geometries (DMG MORI).

4.2 Surface Capabilities

In general, the surface roughness of a 3D printed surface should be less than the layer thickness. The roughness will vary depending on the material, the process, and the geometry of the surface. Major 3D printing services like Stratasys direct include surface roughness in their general tolerances. For example, Stratasys' direct metal laser sintering surface roughness is 350 Ra -

µinch, which is approximately 9 microns (Stratasys). This is approximately one fifth of the 40 micron layer thickness in the Stratasys process and between the ISO N11 and N10 standards.

It is possible to improve the surface finish of metal 3D printed parts. Most major printing companies, such as Stratasys Direct offer a variety of surface finishes on completed parts. Stratasys Direct offers media blasting, tumbling, and hand polishing for its parts (Stratasys). Stratasys claims that surfaces can be improved to a super mirror finish – 0.025 Ra µmeter (Stratasys). It is likely that small internal volumes will be significantly more difficult to improve. In addition to the surface treatments, secondary processes including CNC machining, chemical etching, and wire EDM can be performed on parts (Stratasys).

5.0 CONCLUSION

3D printing is a rapidly developing field. Many of the core patents have expired over the last five years, increasing the competitiveness of the landscape. New venders and service providers are pressuring the established companies into improving their offerings and decreasing prices. 3D printing services, such as Stratasys Direct, are now taking orders for prototypes and small production runs. Any company with CAD capabilities can order a 3D printed part and expect delivery within a week or two.

For waterjet applications, most 3D printers offer a tradeoff in capabilities. 3D printing can produce far more complicated geometries at the cost of increased surface roughness. For certain applications, this trade off may already be worth the increased roughness. However, the field is advancing quickly so that these disadvantages will be further mitigated. One of the latest mitigations was the introduction of DMG Mori's hybrid laser deposition welding and 5 axis CNC machine. This demonstrates that it is possible combine the quality of machined surfaces with the geometry capabilities of 3D printing.

Not all designs or applications will benefit from 3D printing, and it is not a solution to every problem. However, it is likely that some designs will benefit from smoother internal geometry and other previously unfeasible designs will see production. More importantly, the ability to explore exotic geometries will likely lead to innovation.

The widespread availability of 3D printing as a service has lowered the barriers to entry. Anyone with a CAD file and a credit card can order metal parts for around $5 per cubic centimeter of material. While presently available services may not offer all of the recent advances, these commercial vendors offer services with enough features to be useful in many applications.

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