<table>
<thead>
<tr>
<th>Title</th>
<th>The potential of UHP and waterjets for additive manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Mohamed, Hashish</td>
</tr>
<tr>
<td>Date</td>
<td>2018</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/10220/45983">http://hdl.handle.net/10220/45983</a></td>
</tr>
<tr>
<td>Rights</td>
<td>© 2018 Nanyang Technological University. Published by Nanyang Technological University, Singapore.</td>
</tr>
</tbody>
</table>
THE POTENTIAL OF UHP AND WATERJETS FOR ADDITIVE MANUFACTURING

MOHAMED HASHISH
Flow International Corporation
A member of SHAPE Technologies Group
Kent, WA USA 98031

ABSTRACT: Additive manufacturing (AM) is the fastest growing manufacturing technology today with significant funds being spent on many of its aspects worldwide. However, parts made by AM may still need post processing to enhance their characteristics such as density or surface attributes. This paper focuses on metallic parts made by AM and mostly on post processing. While WJ and AWJ are subtractive processes, they can potentially complement AM with several post processing operations such as peening, surface finishing, cleaning, and surface texturing. Also, UHP used to create WJs may be used for densification of AM parts. It was found that cold isostatic pressing (CIP) at pressures of 650 MPa results in almost full densification of copper-based metals made by AM. This has a significant advantage in eliminating the heating process for many metallic parts. However, higher temperatures may still be needed for densification of harder metals which is an area under investigation. The use of waterjets and cavitation for peening has been demonstrated on many metallic materials such as Titanium and Aluminum. Texturing for adhesive bonding using plain waterjets proved to be more advantageous than grit blasting.

KEYWORDS: Waterjet, Ultra High Pressure, Densification, Peening, Surface Finish

INTRODUCTION
3D printing or Additive Manufacturing (AM) is rapidly becoming a mainstream manufacturing process. It is a process where parts are built up layer by layer starting from a computerized model of the part and special software. AM has more than three-decade history for plastic objects while the capacity to make metal objects started in the mid-1990s, Langfeld (2015). The history of this technology can be found in Wohlers Associates (2016). Several processes have been introduced for AM, mainly based on the processes of powder bed or powder feed. It must be mentioned here that AM does not yet produce final parts. Several post processing operations must be performed to achieve the final part. These post processes address three basic areas: a) Surface quality, b) Geometrical tolerances, and, c) material properties. Typical post processing operations may include cutting to separate the part from the base or fixture structure, hot isostatic pressing to reduce porosity, heat treatment, machining of special features, surface treatment, and quality inspection.

In this paper we will address the potential of UHP and waterjets for the AM technology with more focus on the post processing operations.

UHP Technology
To generate ultra-high pressure (UHP) up to 690 MPa and above, special pumps are used and especially when continuous duty cycles are needed. The applications of waterjet cutting and surface preparation depend on the use of reliable UHP pumps. Intensifier and direct drive triplex
pumps are typically used to generate UHP with the intensifier being more capable of higher pressures (~800 MPa) while direct drive pumps are currently limited to ~400 MPa. An intensifier is shown in Figure 1. It works on the principal of pressure intensification. A low pressure acting on a large area results in a higher pressure acting on a smaller area. Conventional variable output hydraulic pumps are used to generate pressures of about 20 MPa over a piston of an intensifier. A plunger with 20 times less area attached to that piston is used to transmit this hydraulic force to water, thus pressurizing it to 400 MPa. In double-acting intensifiers, two plungers are attached to one piston, so while high pressure water is being discharged on one side, low pressure water is charged on the other side. Typical pump frequency is 60-100 cycles per minute.

![Figure 1: Pressure intensifier](image)

Relatively larger UHP pressure vessels such as 200 liters in size are used in the food processing industry to cold-pasteurize certain food products. These vessels are pressurized using intensifier pumps to generate pressures up to 700 MPa which is then held for a period of time to fully treat the food product. The pressure is then relieved to get the food product out of the vessel.

**Waterjet technology**

A high velocity waterjet is formed by pressuring water at pressures up to 600 MPa and then allowing the water to flow through a relatively small diameter orifice. Typical orifice diameters are 0.08 to 0.5 mm, with jet velocities up to 1100 m/s at 600 MPa. Sapphire or diamond (natural or synthetic) are most commonly used orifice materials. Fan type waterjets can also be formed using a specially-shaped orifice geometry. These are typically either metallic or diamond, Hashish 2015. Mixing air with waterjets in a specially designed nozzle results in a waterjet-air jet (WAJ) that has surface preparations effects such as cleaning and peening as will be discussed later. Figure 1 shows these tools. In abrasive waterjet (AWJ) nozzles, abrasives are entrained into a high velocity waterjet to enhance its cutting capability. The abrasives are accelerated and axially oriented (focused) in the mixing tube, which has a length-to-diameter ratio from 50 to 150. Medium and fine size abrasives (mesh 50 to mesh 220) are most commonly used, Hashish (2015). Abrasive slurry jets (ASJ) are formed by pumped a pre-mixed mixture of water and abrasives. This has a few benefits over AWJ such as smaller diameters, finer abrasives, and more power density making them more efficient for cutting and finishing.
The above tools have potential for processing AM parts as discussed next.

**POTENTIAL APPLICATIONS**

The potential post processing applications for AM parts to be discussed here are:

**Densification**

Pressure densification by hot or cold isostatic pressing has been known in powder metallurgy for decades. It is different than mechanical pressing, which is unidirectional in the fact that pressure is applied around the entire part in a fluid medium. HIP was first introduced in the 1980s by Battelle Institute as a technique for a diffusing bonding of nuclear fuel element assemblies, Atkinson and Davies (2000). Soon after it was used as a method for sintering and densification. In the HIP technology, Bocanegra-Bernal (2004), high temperature and high pressure are simultaneously applied to workpieces. HIP can be used directly to consolidate a powder to further densify a cold-pressed, sintered, or cast part. The HIP process, which subjects a component to elevated temperatures, generally 1000C to 2000C, and pressures at the ~100 MPa level eliminate the internal porosity which is essential to maximize the properties and working life of the component. The use of highly elevated temperatures, however complicates, the HIP process and affect the cycle time of parts specially recently with the introduction of additive manufacturing to become a main stream technology. First a large number of parts must be fabricated before simultaneous ‘Hipping” for reduced cost per part. This large batch processing is time consuming and not conducive to modern manufacturing practices. Also, using higher temperatures limits the pressure levels and increase the handling issues. Accordingly, the use of cold (below 500 C) or warm (500 to 1000 C) isostatic pressing (WIP), but at pressures reaching 800 MPa may be of great benefits.

We have conducted tests on binder-jetted 3D-printed copper sample provided by Virginia technological University to explore cold isostatic pressing (CIP) for densification. A HIP process was shown to improve final part density from 92% (of theoretical density) in the as-sintered

<table>
<thead>
<tr>
<th>Waterjet: 0.25-mm at 400 MPa</th>
<th>FanJet: 0.5-mm at 350 MPa</th>
<th>Water-Air Jet (air is injected into a waterjet)</th>
<th>Abrasive Waterjet</th>
<th>Abrasive slurry Jet</th>
</tr>
</thead>
</table>

Figure 2: Waterjet tools
condition to 99.7% after HIP, Kumar et al. (2016). It was found that CIP at pressures >700 MPa is sufficient to densify binder-jetted copper from the sintered state.

For food cold-pasteurization, relatively small monoblock pressure vessels (up to ~45 liter) have been developed for operating at pressures reaching 800 MPa using a swing yoke approach, Hashish (2000). Smaller 2-liter units with about 50-mm bore diameter have also been developed. These relatively small sizes will be suitable for rapid HIP or CIP processing of small batches of AM parts.

**Waterjet peening**

When a waterjet impacts a material surface, it causes either cutting of the target material or plastic deformation in the deep surface layer. Above a certain impact stress threshold, the impact process induces compressive residual stresses which improve fatigue life and thus it is attracting great attention in the aero engine industry. Fluid-fluid jets has also been demonstrated for peening. In one test, Chillman, et al. (2010), a waterjet was traversed over an aluminum a material at an impact angle of 90°. The nozzle was set to move at varied standoff distances from 10 mm to 150 mm steadily with a 300 mm transverse distance. The surface compressive residual stress was measured using x-ray diffraction. The obtained results were compared to dry shot peening indicating a 20% increase in micro-hardness. Similar tests were performed on titanium, but at higher waterjet pressures, up to 600 MPa, resulting in the same effect. Currently, there are no waterjet-peened production parts in the industry as shot peening has been established for many years for many parts. However, for AM parts, waterjet peening can be highly beneficial as AM parts are typically complex with narrow internal and external features which are easy to access with pure waterjets. Also, no specific peening processes have been established yet for AM parts which is early in the approval cycle.

**Cavitation peening**

It is common that cavitation produces damage in parts exposed to this phenomenon such as propellers and other hydraulic machinery. However, the cavitation impact may be used to peen surfaces similar to shot peening, but without any shots. Peening using cavitation impact is called cavitation peening, Soyama et al., (2009). A cavitating jet is normally produced by the flow of a water jet into a water-filled chamber. Parts submerged in water, may then be subjected to the collapse of the bubbles on their surfaces. To simulate submerged conditions, a water shroud may be used around a waterjet to crate cavitation bubbles which then can be carried and collapsed on a metal object. Cavitation peening was tested by Soyama (2009) on different metals with significant improvements. For example stainless steel 316 fatigue life improves from $10^6$ cycles to $10^7$ cycles at 370 MPa bending stresses.

**Texturing**

While the surfaces of AM parts may be textured due to the printing process, the surface morphology may not be suitable for coating. Waterjets have been used for texturing of surfaces, Taylor (1995) to prepare them for coatings especially in the automotive industry. Waterjets are also being introduced into the jet engine industry. This include continuous and pulsed jets, Vijay, et al. (2015). Among the advantages of waterjet-prepared surfaces are: higher bond strength, adjustable surface finish is possible, no dust, lends itself to automation and scaling up, cleans the surface, and access to tight area as may be encountered in AM parts.
Unlike grit blasting which results in the entrapment of particles, waterjet profiling cleans the surface. It is hypothesized that waterjet roughening produces a favorable surface morphology for bonding because it creates undercuts which help locking in the coating.

The use of air-waterjets, Chillman, et.al. (2010) to prepare titanium and aluminum surfaces has been investigated. In this approach, air is mixed with a round jet in a downstream tube to form a droplet jet. Controlling the air flow rate, the droplet structure of the jet changes and thus jet sensitivity to stand off distance can be varied and thus the ability to access tight deep spots on an AM parts is gained.

Surface finish improvement

The use of high-velocity free streams of liquid-abrasive jets has been demonstrated for polishing, Hashish (1992). A turning process was used to demonstrate that the surface finish can be improved for rods of glass and boron carbide. Aluminum oxide abrasives were used with gradual reduction in grit size from 220 mesh to about 400 mesh. The progressive reduction of grit size to improve surface finish is still required with fluidjet polishing, but the quantitative increments of grit size reduction are significantly different than with conventional polishing.

It is expected that for polishing of AM parts with complex geometries both kinematics and fluid erosion techniques must be integrated to expose the multitude of surfaces and passages of an AM parts to the abrasive particles and in a desired orientation. This obviously require additional studies and research but promising for faster rates of processing.

Cleaning

Waterjet cleaning covers many applications in a wide range of industries ranging from farming to shipyard to microelectronics. For AM parts there is a need to clean off the parts from the powder that may still be attached to the external and internal surfaces. Vacuum is used to pull out loos particles but not capable of removing bonded particles. Waterjets have been demonstrated to remove rust of ship surfaces, flash from castings, burrs from machined parts, and TBC coating off jet engine parts, and thus it is highly promising to remove the bonded powder from AM parts. Due to the fact that waterjets are relatively small in size, they can access small cavities and holes effectively. It was demonstrated that waterjets can clean holes in jet engine parts such as shrouds, vanes and nozzles after re-coating them with TBC.

CONCLUSIONS

The UHP and waterjet technologies are tools that can be used in the AM industry for both technical and economic benefits. While a few processes have been successfully demonstrated on conventionally-machined parts, some other processes need to be developed for AM parts.

- UHP in the range of 600 to 800 MPA is promising to densify AM parts at less temperatures that currently being used in HIP processes at 300 MPa pressures.
- Waterjet and cavitation peening of AM surfaces are highly promising and have been demonstrated on Aluminum, Titanium, and Steel. More work is needed however to minimize the erosive effect of the liquid treatment process if the surface morphology is unacceptable.
- Waterjets have been proven to texture surfaces for coating. They can be used to modify the surface morphology of AM parts if coating is to be applied on AM parts.
- Waterjet cleaning is highly promising for AM parts to reach tight spots.
ACKNOWLEDGMENTS
The author would like to acknowledge the work by Greg Mital of Flow International on the work conducted on copper alloy densification in cooperation with Virginia Tech. University.

REFERENCES


Kumar, Bai, Eklund, Williams; (2016) “Effects of Hot Isostatic Pressing on Copper Parts Fabricated via Binder Jetting”; 45th SME NAMRC 45, LA, USA


