WHITE PAPER

Considerations for Optimizing Surface Finishing of 3D Printed Inconel 718

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CONTENTS

I. ADDITIVELY MANUFACTURED METALS AND POST-PRINTING

Additive manufacturing (AM) of metal and metal alloy parts offers a way to manufacture complex metal geometries with new design freedoms previously unobtainable with traditional manufacturing methods. Designs that would have been limited by geometry restrictions and incurred extensive mold, fixture, and labor costs, can now be made with nearly limitless design freedom to high standards using a wide range of metal powders. While prototyping metals with AM technologies has proven quite valuable, it is no longer solely for design validation. It is now being used for the production of components for the most demanding applications in aerospace, medical, dental, and industrial industries.

This added value does not come without its challenges, however. Many of these challenges come in the post-print stage after the geometry has been generated. Some of these common challenges include, but are not limited to:

- Removing unwanted metal powder
- Removing unwanted print material
- Removing unwanted support material
- Reducing the surface roughness
- Removing oxidized surface material
- Improving the luster of the part
- Passivating the surface
- Relieving stress

In addition, each print technology and material can add further complexity to these objectives. Current technologies for printing 3D metal applications include powder bed systems such as DMLS (direct metal laser sintering), EBM (electron beam melting), and SLM (selective laser melting), or powder feed systems such as LC (laser cladding), LMD (laser metal deposition) and DED (directed energy deposition). Across each of these technologies, some of the most popular alloys being additively manufactured today include titanium, aluminum, stainless steel (304, 316), AlSi10Mg, Ti6Al4V, nickel superalloys (i.e., Inconel 718, Haynes 282, Hastelloy), CoCr, and carbon steel.

PostProcess Technologies has developed a solution to smooth the surface profile for one particular metal produced by AM, nickel superalloy Inconel 718. To achieve this success, a number of challenges associated with Inconel 718, additively manufactured metals, and AM processes had to be overcome. Before reviewing the process and related case studies, it is essential to understand all of the challenges associated with metals and alloys, metal surface finishing, and metals made by additive manufacturing.

II. CHALLENGES OF SURFACE FINISHING AM METALS AND ALLOYS

Surface finishing of metal parts often relies on expensive processes, requiring a large amount of manual labor or the use of hazardous chemicals. These methods range from mechanical methods such as machining, hand sanding, blasting, tumbling, and chemical surface treatments like descaling and pickling.

To meet metal specifications, the approach may require a combination of these processes to address the numerous challenges that additively manufactured metals create. Several factors make this a difficult endeavor. Five common challenges are explored below:

1. Part density, hardness, and corrosion (chemical) resistance
2. Different and varied grain structures that change with thermal treating processes
3. Print technologies resulting in different mechanical and chemical properties
4. Print orientation affecting the rate of removal and surface finishing of the part
5. Alloys having very different mechanical and chemical properties from the pure metal

Density, Hardness and Chemical Resistance

Density and hardness properties for Inconel 718 are compared to common AM metal alloys along with additional material attributes in Table 1. Comparatively, Inconel 718 is one of the more dense materials and is twice as hard as stainless steel. This hardness, combined with temperature and corrosion resistance makes it an especially challenging material to address surface roughness.

Table 1 - Typical properties of common AM metal alloys

Metal Alloy	Material Properties	Primary Composition	Hardness HRC	Density g/cm^3
AlSi10Mg	Corrosion resistance, high strength-to-weight ratio and temperature resistance	Al, Si, Mg	60-70	2.68
Ti6Al4V	Corrosion resistance, strength, temperature resistance and weight reduction	Ti, Al, V	30-40	4.42
Inconel 718	High strength, excellent temperature and corrosion resistance	17-21% Cr 50-55% Ni 20-30% Fe	32-40	8.19
Stainless Steel	Corrosion and crack resistance	16-18% Cr 10-14% Ni 65-75% Fe	16-20	8
CoCr	High tensile strength & hardness; bio-compatibility	50% Co 50% Cr	40-50	8.6

Grain Structure

The grain structure of Inconel 718 is important to this superalloy's strength, hardness, and chemical resistance. Specifically, the grain structure of a metal is an arrangement of differently oriented grains, surrounded by grain boundaries (Figure 1).

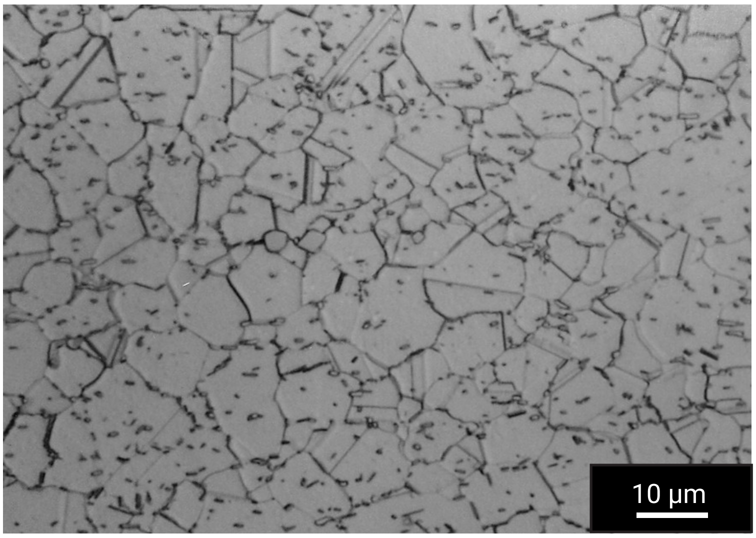
When metal cools and solidifies from the molten state, crystals grow; the slower the cooling, the larger the crystals. The grains form as a result of solidification or other phase transformation processes. Grain shape and size can be changed through thermal treatment processes. Normal crystalline metal grain size varies from 1μm to 1000 μm. The grain structure and grain boundaries determine the chemical, electrical, and mechanical properties (i.e., strength, weldability, ductility, fatigue) of the metal or alloy.

In metals, a **grain** is a small region of the metal with a given and continuous aligned crystal lattice orientation, or group of formed crystals.

The **grain boundary** refers to the interface between two grains, separating it from the other grains of the metal.

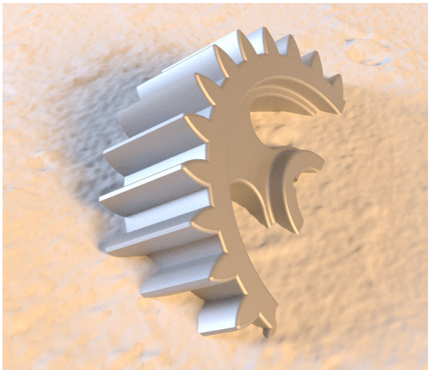
Grain structure control for Inconel 718 as well as other metals are challenging for additive manufacturing. Optimization requires the control of grain morphology through grain size refinement in the powders used in AM, as well as processing parameters when printing the parts such as melt temperature or laser size and shape. Additionally, the user should be aware that these properties can be altered during the post-print phase.

Figure 1 - Microscopic view of superalloy grain structures and boundaries (Reference 1)



Impact of Print Technology

Powder bed technology illustration



The method that the alloy is printed by must also be taken into account when addressing the surface profile. With metals, two common additive methods to compare are powder bed and powder fed. DMLS, used to print Inconel 718, is a powder bed system that uses a powder reservoir and a coating mechanism to spread a fresh powder layer onto a substrate plate. The typical layer thickness of this technology ranges from 20 μm to 80 μm. A laser traces the cross-section to sinter layer by layer, alternating with the recoating blade until the parts are complete. Powder fed technologies, such as directed energy deposition, use the same powder feedstock, but the material is extruded and fused instead of sintered. The powder flows through a nozzle and is melted from a beam on the surface of the treated part. While precise, layer thickness with powder-fed technologies can rise well above 100 μm.

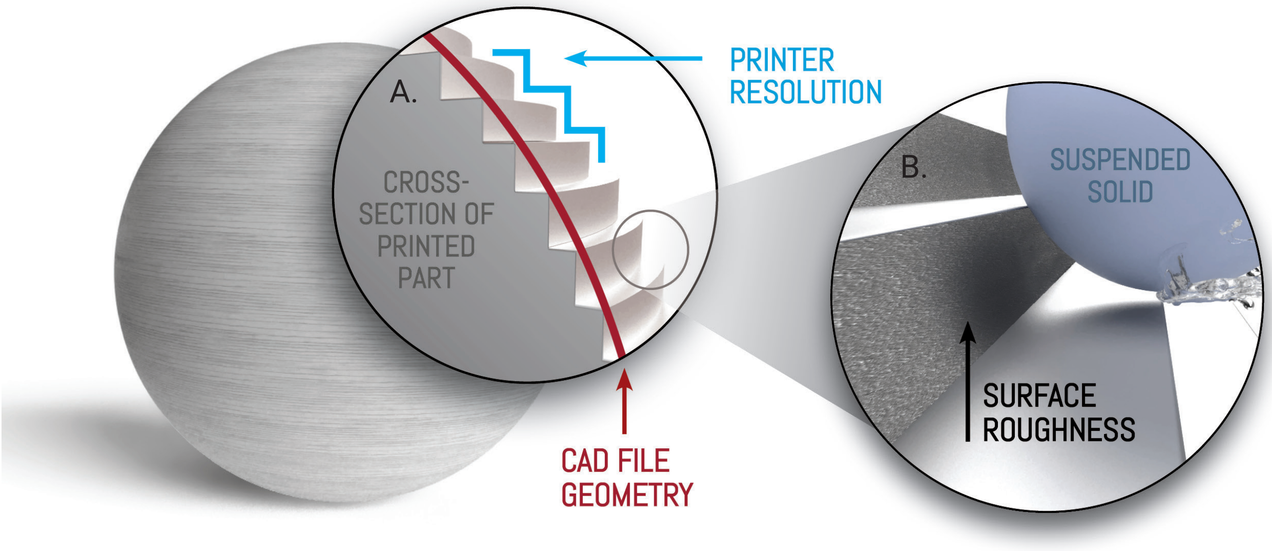
The process used to print the part affects crystal and grain structure growth and size, printed layer size, and ultimately, the properties of the part. For example, because the DMLS process uses higher energy, problems arise with instabilities in the melt pool that can lead to part shrinkage. Likewise, grain growth during post-processing heat treatment can be restricted by the presence of nano-scale oxide particles formed in-situ during the print process. Similarly, multiple melting-solidification cycles during AM processes result in complex microstructures potentially with discontinuities, mixed grains, disordered phases, and abnormal compositions.

In both of the aforementioned technologies, parts are generated in discrete layers. The result of this can be a noticeably rough surface profile. Two main factors contribute to this:

1. Although the CAD geometry is smooth, printer resolution limitations result in offset layer edges leading to stepping along the surface profile (Figure 2A). This phenomenon is magnified for round or curved features where the layers can create a very rough, uneven outer surface. Measuring roughness perpendicular to the layer lines will capture this profile factor.

2. The print surface itself (Figure 2B) is subject to roughness due to the solidification process, particle size, splatter, and other process factors. This can be measured along flat surfaces where layers are not present or parallel to the layer itself.

Figure 2 - Depiction of general stepping and roughness cross-section



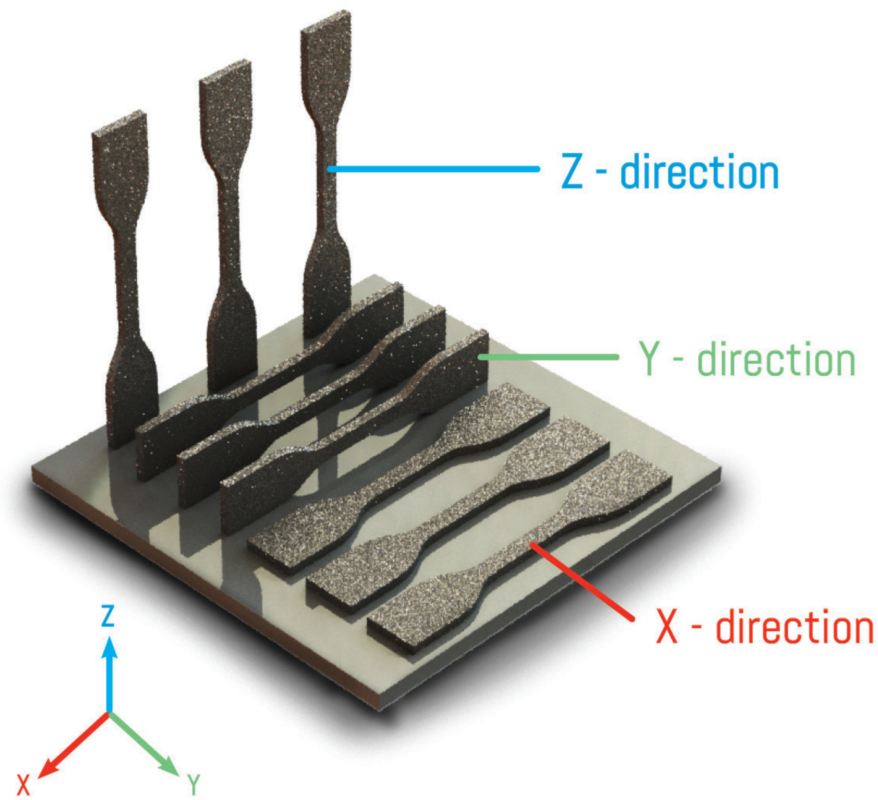
These profile factors make selecting the correct chemistry and abrasive type, size, hardness (note the suspended solid represented in Figure 2), and processing parameters very important considerations to achieve the target surface profile. This will be explored further in Section III.

Print Orientation

Typically the aforementioned technologies either leverage densely packed powder beds and/or support structures to print geometry in nearly any orientation. This is a critical decision for the user because the print orientation has been shown to affect mechanical properties, chemical and corrosion resistance, and the conductivity of the printed part both before and after heat treating. This further increases the complexity of material removal along the surface profile of the geometry while trying to maintain its integrity.

To demonstrate this concept in a simple graphic, Figure 3 highlights three standard orientations: an X-direction (flat), a Y-direction (on edge), or a Z-direction (upright), for a standard tensile bar. Although a seemingly harmless decision, different stepping patterns will be generated in each of these basic print orientations. This can have a major impact on surface roughness, especially as geometries become more complex.

Figure 3 - Display of 3 possible print orientations



Alloy vs. Pure Metal

Adding other elements to a metal significantly changes the base metal's properties such as strength, creep resistance, oxidation and corrosion resistance, and weldability. Inconel, a family of austenitic nickel-chromium-based superalloys was evaluated in the 1950s for an opportunity to develop a material for supercritical steam power plants. The product goals for the development were weldability, high creep resistance, tubing fabricability, and to be non-age hardening while meeting ASME Boiler Code properties. The strengthening effects of various amounts of the common major alloying elements, i.e., chromium, molybdenum, niobium, aluminum, and titanium, was done to an Inconel alloy 600 base. The strengthening was done using molybdenum and niobium in combination with varying amounts of nickel. The results of this development were corrosion resistance, high strength, good weldability, and good formability - Inconel 718 superalloy (Reference 2).

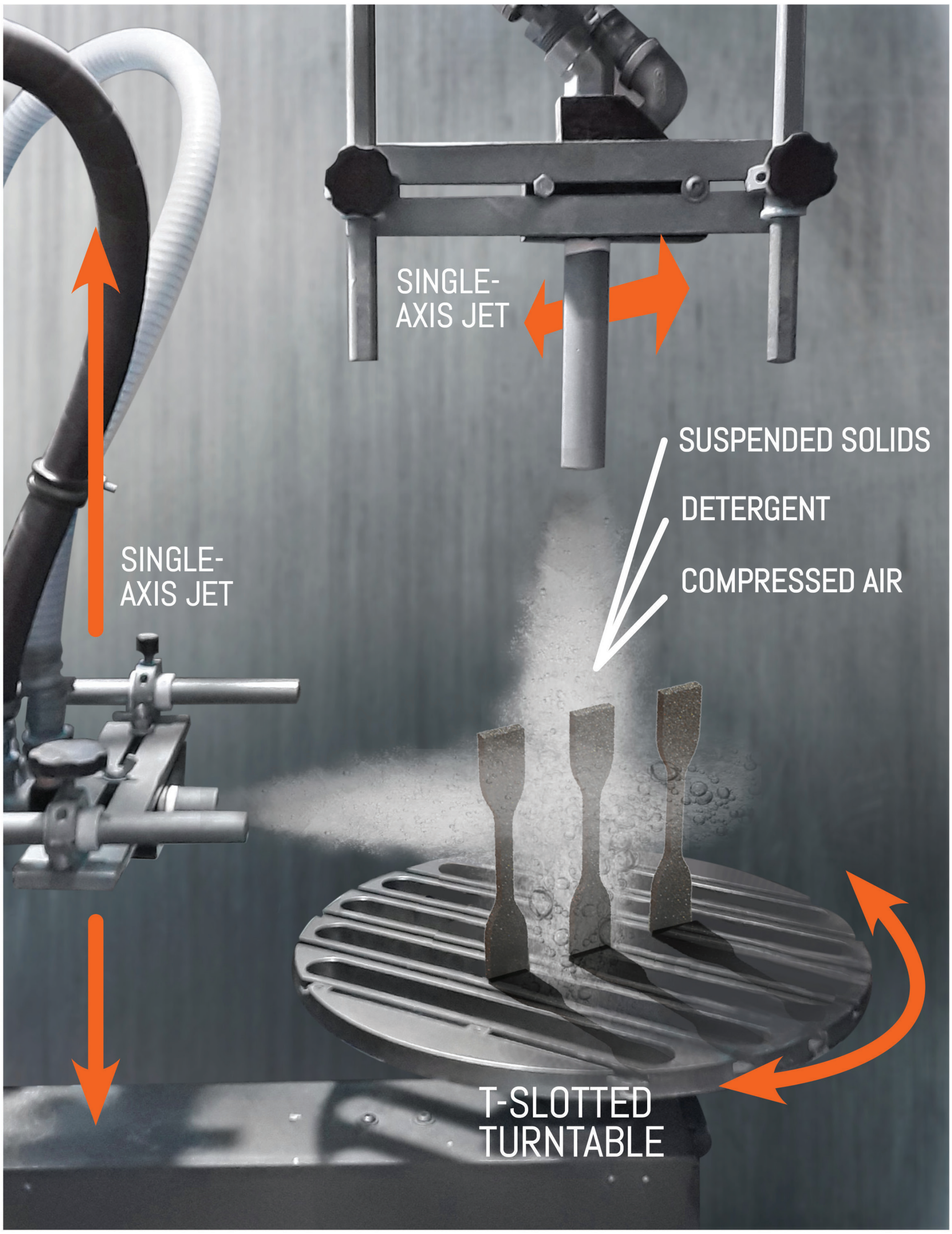
Inconel 718 (55Ni-21Cr-5Nb-3Mo) is a nickel-based superalloy where the addition of niobium led to overcoming cracking problems identified during welding. This superalloy is precipitation hardened to maintain high strength and good ductility up to 1300°F (704°C) and has relatively good weldability, formability, and cryogenic properties compared to other precipitation hardened nickel alloys. Inconel 718 is non-magnetic, maintains good corrosion and oxidation resistance, and is used for parts requiring high resistance to deformation and stress cracking up to 1300°F (704°C), and oxidation resistance up to 1800°F (982°C). With these properties, very hazardous chemicals such as hydrofluoric acid (HF) or aqua regia (HCl/HNO_3) are usually required to remove material from the surface of Inconel 718 as a part of surface finishing. Inconel 718 has become one of the most widely used nickel-based superalloys in the aircraft engine industry. It is used in many critical aircraft engine components, accounting for over 40% of the finished modern aircraft engine.

To truly make additively manufactured Inconel 718 a functional material in a production environment, it is imperative to address the surface profile in an automated fashion while meeting industry-specific requirements. The challenge is overcoming the mechanical properties, chemical resistance, and inherent process challenges presented.

III. LEVERAGING TAF TECHNOLOGY FOR NEW APPLICATION DISCOVERY

PostProcess has demonstrated the capability to improve the process of finishing AM surfaces using a data science approach. PostProcess developed a solution that combines a new detergent, specific to additively manufactured Inconel 718, with the patent-pending Thermal Atomized Fusillade (TAF) technology, depicted below in Figure 4. The entire process is software controlled through PostProcess' AUTOMAT3D™ platform allowing for the highest level of process predictability, insight, and control. The hardware configuration that houses the TAF technology is PostProcess' DECI Duo. The machine is equipped with two single axis jets that emit compressed air, detergent, and suspended solids at variable software-regulated pressures. Additionally, the DECI Duo is equipped with a T-slotted 360° rotating turntable designed for flexible fixturing. The rotation of the table makes for a third axis of motion, providing maximum surface exposure for the geometries being processed. Managing multiple sources of energy is the first key component of PostProcess' AM metal finishing solution.

Figure 4 - Schematic representing DECI DUO & TAF technology (fixturing omitted)



To manage these energy sources, it is the AUTOMAT3D software that propels the solution into the digital era, dissimilar to other metal finishing options. Agitation Algorithms were developed for this application, laying the foundation for a predictive, data-driven approach when finishing AM metals. The software monitors and controls the speed and direction of the axes, processing temperature, and air and liquid pressures throughout the duration of the cycle to ensure the chemical and mechanical energy sources are utilized effectively. AUTOMAT3D also allows users to save parameters to simplify machine preparation and repeatability. The software will also keep track of run time allowing for scheduled preventive maintenance, in turn reducing downtime and creating a process supportive of production-level throughput.

Identifying a suspended solid that combats the challenges presented by Inconel 718 and aligns with the outputs of the print technology, in this case, DMLS, is integral. A ceramic-based aggregate with high toughness was chosen to address the material hardness. To correlate most effectively with the surface roughness created by the ranges of layer thicknesses associated with DMLS, a size considered on the larger end of the suspended solids spectrum was chosen. Additionally, the abrasive is chemically inert, meaning it will generally not lead to contamination of the build material or detergent.

A key discovery to complement the existing hardware and software package was the formulation of a new proprietary detergent. The formulation stems from the analysis of Inconel 718's physical and chemical properties. This advancement, a mildly acidic solution, introduces etching to supplement the overall surface finishing process while being void of the hazardous qualities associated with the alternative chemistries that are currently being used in the industry. The detergent etches the surface to provide the chemical rate of removal (cRoR), allowing the suspended solids to more effectively abrade the surface of the geometry, providing the mechanical rate of removal (mRoR). This solution's multi-faceted approach allows the process to run at lower thermal energies, mitigating the risk of affecting the grain structure of the part.

This flexibility of the patent-pending solution allows the user to digitally retool to satisfy a range of requirements. For instance, if the goal is to remove roughness from the surface profile, the process can be completed with a single set of repeatable parameters. Further reduced surface roughness, akin to a polish-level roughness average (R_a), can be achieved through software adjustments of air and liquid pressure along with speed and direction of each axis. This solution allows for shortened cycle times and increased operator safety while achieving the consistent and repeatable results necessary when dealing with metals and their stringent application requirements.

CASE STUDIES AND VALIDATION

With numerous possible combinations of print technologies, materials, and post-printing challenges and goals, it is crucial to assess each situation uniquely to understand and validate the post-printing results. The following study focuses on addressing the surface profiles of the nickel superalloy widely used in the aerospace industry, Inconel 718, printed with DMLS technology:

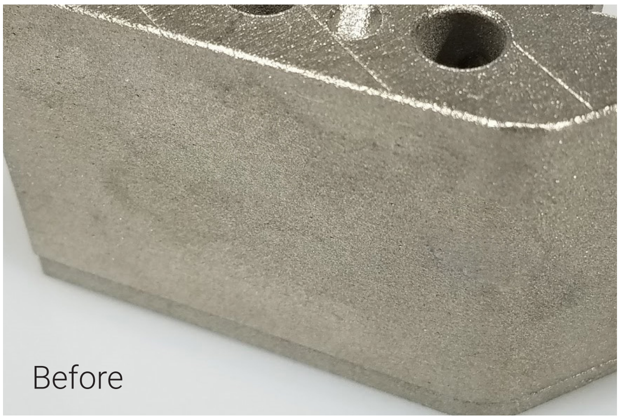
Print technology:	DMLS
Print material:	Inconel 718
Post-printing:	Surface roughness (roughness average, R_a)

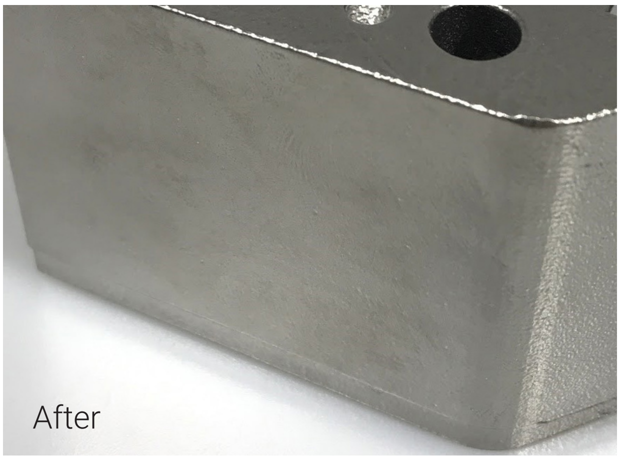
For each round of validation testing completed, PostProcess used parts of different geometries and starting R_a values, along with varying R_a targets, in order to deliver a thorough data set and capability assessment. Based on these different objectives, the Agitation Algorithms were varied accordingly. Reducing the surface roughness in this application requires elevated temperatures, liquid, and air pressures. These elevated ranges increase the mechanical energy in the system resulting in a rapid rate of removal (RoR).

To measure the surface profile, a profilometer was utilized which drags a stylus across the surface of the geometry to measure all of the deviations in a specified region. The profilometer then takes the average of all the deviations and provides a roughness calculation of the measured surface. Roughness values vary depending on the direction and geometry upon which the stylus is established. The measurements provided were taken in the direction perpendicular to the print layers to capture profile variations from both layer resolution and print surface roughness. Key data points in each of the shared case studies include the before and after roughness averages with reduction percentage, operator time, and machine cycle time.

INCONEL 718 CASE STUDIES:

Case 1


Before


After

Start R_a	**623 µin (15.8 µm)**
Finish R_a	**73 µin (1.85 µm)**
% R_a Reduction	**88%**
Operator Time	**5 Minutes**
Machine Cycle Time	**3 Hours**

Case 2


Before


After

Start R_a	138 µin (3.5 µm)
Finish R_a	39 µin (0.99 µm)
% R_a Reduction	72%
Operator Time	5 Minutes
Machine Cycle Time	1.75 Hours

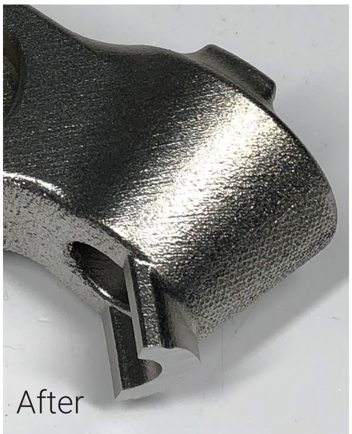
Case 3


Before


After

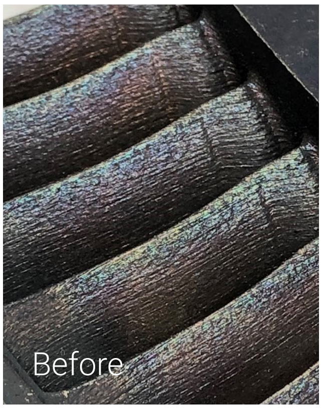
Start R_a	228 µin (5.8 µm)
Finish R_a	100 µin (2.5 µm)
% R_a Reduction	57%
Operator Time	5 Minutes
Machine Cycle Time	3 Hours

Case 4



Start R_a	200 µin (15.8 µm)
Finish R_a	80 µin (1.85 µm)
% R_a Reduction	60%
Operator Time	5 Minutes
Machine Cycle Time	15 Minutes

Case 5



Start R_a	315 µin (8 µm)
Finish R_a	71µin (1.85 µm)
% R_a Reduction	77%
Operator Time	5 Minutes
Machine Cycle Time	0.8 Hours

The overall reduction in R_a ranged from 57% to 88%. In each case, the final R_a was less than or equal to 100 µin (2.5 µm). As previously stated, varying processing algorithms were utilized to adapt to geometry parameters such as starting profile roughness, size of geometry and features, and print orientation. These factors resulted in machine cycle times ranging from 15 minutes to 3 hours. However, a key metric of operator time remained consistent as the only operator requirements to run a cycle are selecting an Agitation Algorithm, fixturing the part before the cycle, then part removal and rinse upon cycle completion.

In the instance of Case 2, a smoother surface of less than 1 µm (39 µin) was targeted. For this objective, a second Agitation Algorithm with lowered mechanical energy was chosen for a reduced RoR. To prepare for this additional processing, the adjustments are solely digital, resulting in a negligible impact on operator attendance time. Case 4 and 5 introduced considerably smaller and thin-walled features. Maintaining the integrity of the geometry without rounding sharp corners is an additional benefit.

IV. CONCLUSION

In conclusion, PostProcess Technologies' discovery, focused on additively manufactured Inconel 718, is an enhanced solution for smoothing surface profiles. It has demonstrated the capability to address varying levels of initial surface roughness across a variety of geometries without sacrificing feature detail. This process will improve the user experience through automation while decreasing the risks associated with current laborious and chemically hazardous practices conventionally used in the industry. PostProcess' patent-pending solution rooted by TAF technology, a software-driven configuration leveraging suspended solids and a new detergent, introduces a new method for processing metals to support the growth of additive manufacturing at product-level volumes.

(1) METALLOGRAPHIC TECHNIQUES FOR SUPERALLOYS, July 2004, Microscopy and Microanalysis 10, George F. Vander Voort1, Elena P. Manilova2, Gabriel M. Lucas, Buehler Ltd., 41 Waukegan Road, Lake Bluff, IL 60044 USA

(2) Superalloys 71.8,625 and Various Derivatives, Edited by Edward A. Lmia, The Minerals, Metals & Materials Society, 1991

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