

# Review of Internal and External Surface Finishing Technologies for Additively Manufactured Metallic Alloys Components and New Frontiers

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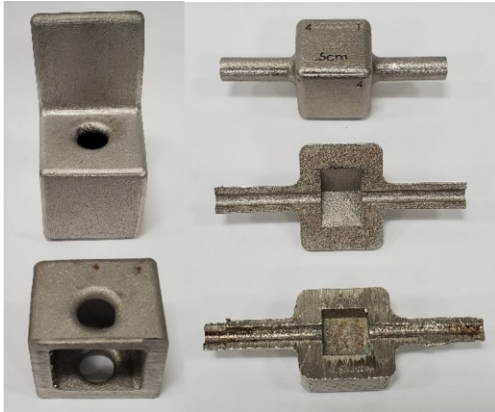
**Abstract** Surface finishing in additive manufacturing (AM) is a technological bottleneck. The field of surface finishing of AM parts is vast because it not only focuses on roughness reduction in the hard-to-access internal surfaces but also includes the scope of adding coatings and sensors. Even though metal AM component is reaching the density and bulk microstructure at par or even better than conventionally produced components, but adverse impact of surface roughness and imperfections is becoming the major obstruction. It is observed that external and internal surface roughness of AM components is a high probability cause of many unavoidable issues such as corrosion, incorrect tolerance estimations during the build stage, and the fatigue failure of parts before the expected life cycle. At present AM field mainly focus on improving and enhancing the internal and external surface roughness to pass the stringent qualification requirements for actual applications. To address these challenges, researchers worldwide are conducting many experiments and developing different surface finishing techniques. This paper reviews the state of art knowledge and processes of different surface finishing technology that can be applied to AM metal components. This article mainly highlights several liquid-based surfaces finishing approaches to develop promising surface microstructures on interior and exterior surfaces as a micromachining tool. The future of making strong and self-monitoring AM component require broadening of surface finishing field and including advanced topics such as coatings and adding sensor technology. We also discuss new frontiers and the scope of future work in the surface finishing field to bring attention to related concerns and possibilities associated with making smart and strong AM components for 21<sup>st</sup>-century integrated engineering systems.

**Keywords:** Additive manufacturing, surface finishing, metal components, roughness, fatigue, coatings

## 1. Introduction

Additive manufacturing (AM) is a technology of building components layer by layer from a CAD-generated 3D model and fusing the material [1] for a wide range of disciplines [2]. There are many options for AM technologies available on the market, and some other approaches are developing fast. AM has been utilized for the custom manufacturing of a wide range of materials, such as plastics [3], concrete [4], biological tissues [5], and metals [6]. However, AM of metals and metallic alloys is of particular significance because of the field of applications involving high cost, safety, and national defense interests. The choice of AM process may depend on the material, technology, price, country of origin, desired accuracy, etc. [7]. AM is broadly classified as Fused Deposition Modelling (FDM), VAT Polymerization, Binder Jetting, Directed Energy Deposition (DED), Selective Laser Sintering (SLS), and Laminated Object Manufacturing (LOM) [8]. Interestingly, AM of metal components or metal-bearing materials is very crucial for making innovative and high-impact use of this technology. Several processes which are primarily known for polymers and other materials are being tailored to produce metal-bearing additively manufactured (AM) components [9]. All the AM techniques invariably produce significant internal and external surface roughness, and many critical properties like corrosion resistance depend on metal. Depending on AM methods, the level of roughness can be very high. For example, the powder bed fusion (PBF) approach can yield as high as ~20  $\mu\text{m Ra}$ , and any component with this roughness level will not qualify for any practical application. The roughness level for the internal surfaces can be of the same order or higher depending upon the engineering design and AM techniques utilized for the manufacturing. Designing a surface finishing process must be considered based on internal surfaces. For example, figure 1 shows two AM 316 stainless steel samples involving internal surfaces accessible via a tight 2 mm diameter channel and another sample with ~ 10 mm diameter opening. External surface finishing may be performed via the same method on both samples, but one need to

engineer custom-designed method for internal surface finishing of the sample with a 10 mm long 2 mm diameter channel. Advanced surface finishing where one needs to produce a coating on the interior surface of AM component, will be even more complicated and exponentially more challenging. Currently, the surface finishing field is mainly focused on reducing surface roughness. Several surface finishing methods have been applied to AM components to improve the internal and external surface morphologies. The nature of surface finishing methods varies significantly and has been the focus of review articles from multiple perspectives [10][11]. After a brief overview of various AM concepts, this paper investigates different surface finishing techniques for metallic components. We have mainly focused on liquid-based surface finishing because of its unique advantages related to the improvement of hidden internal surfaces of metallic AM components. This paper also discusses the advanced topics in the surface finishing of AM components that may motivate research in other directions beyond surface roughness improvement.

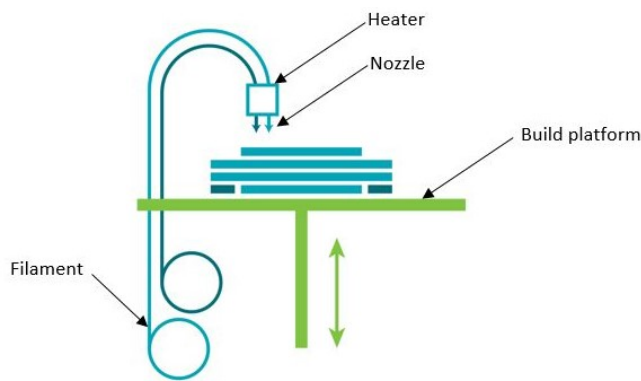


**Fig 1.** AM stainless steel objects showing outer view and internal surface and channel. Samples were produced by the EOS M280 laser sintering machine.

## 2. The process and characteristics of AM technologies

### 2.1 Fused Deposition Modelling (FDM)

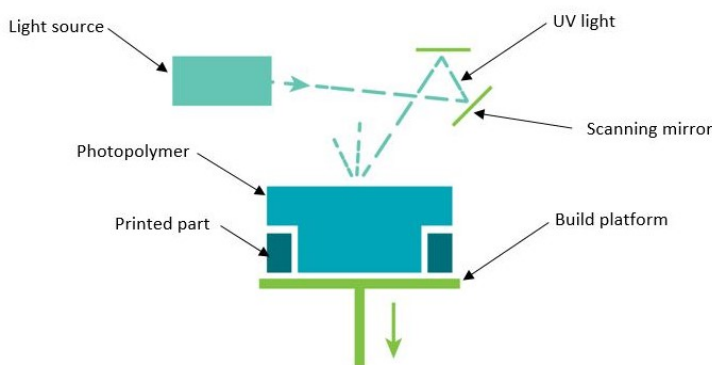
FDM stands for Fused Deposition Modelling. In this technology, deposition occurs from a continuous filament of composite or thermoplastic material [12]. FDM has been extensively used for conventional and newly formulated plastics keeping AM technologies in sight [13]. In FDM printing, a particular thermoplastic filament is heated to its melting point, [14] and the extruder pushes the melted material through the nozzle in a particular layer-by-layer arrangement to finally form a desired 3D solid object. FDM has been considered for many important areas, such as pharmaceuticals [15]. FDM has tremendously helped the education of AM field in elementary school to higher education institutions [16]. FDM has a variety of benefits and drawbacks. Some of the benefits are easy setup and low operating costs [17], a large variety of printing materials [18], quick prototyping [19], and simplicity to use [20]. FDM machines are available with a range of costs, sizes, [21] and areas of utilization [22]. A range of high-caliber AM machines is manufactured to work with industrially relevant plastics for real applications. One significant advantage of FDM is that a vast range of raw materials can be designed to produce a variety of plastic AM components with exciting properties. Despite the many advantages, there are also some disadvantages. The process can leave visible layer lines, printing materials are toxic at melting temperature, and the nozzle is supposed to be in motion to prevent bumping up[23][24]. Additionally, plastic AM parts may not fit well with metal AM components. FDM parts cannot serve all the AM applications requiring high temperature applications.



**Fig 2.** Schematic diagram of Fused Deposition Modelling.

## 2. 2 VAT polymerization

VAT polymerization is one 3D printing process that builds 3D objects using light-activated polymerization to cure photopolymer liquid resin [25] selectively. VAT has been extensively applied to bioprinting and has been considered for practical application by addressing regulatory challenges [26]. A photopolymer, also known as light-activated resin, is a type of polymer that changes the way its molecules behave when it is subjected to light [27]. Typically light is in the ultraviolet or visible part of the electromagnetic spectrum [28]. Unlike FDM technology, the printer does not deposit as a solid object. In contrast to the FDM printing placing solid plastic on the flat bed, a highly viscous material is deposited onto the 3D print bed. Then the part must then be cured to develop a hard texture and form the desired object[29]. Some of the VAT polymerization advantages are a high degree of detail and precision printing, superior overall quality [30], application in organ scale fabrication [31], and utilization of innovative polymer chemistry for multi-material printing [32]. Some disadvantages are high cost, lack of available photo-resin material choices, Inadequate strength and durability after printing, resins can still be impacted by UV light, and resins can warp and bend over time [33].



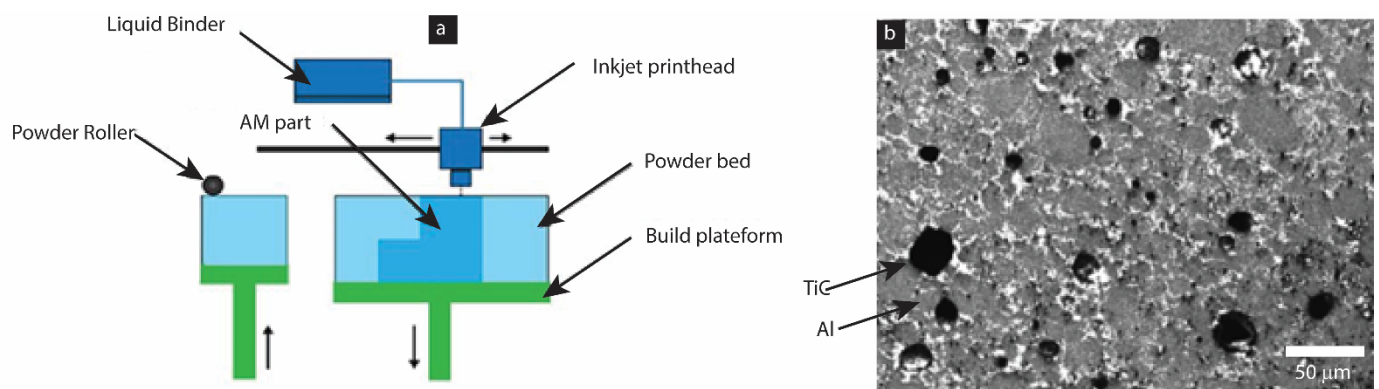
**Fig 3.** Schematic diagram of VAT polymerization

## 2. 3 Binder jet printing

### 2. 3 Binder jet additive manufacturing (BJAM)

Binder jetting, also known as inkjet binder 3D printing, is the fastest additive manufacturing method for producing highly dense [34], functional precision parts in large quantities [35]. Liquid binding agents are utilized for joining powder particles. The binding agent is a sandwich between the metal powder material starting from the first layer of the build material [36]. Binder jetting involves many process parameters impacting the quality of finished components [37]. Binder-jet AM followed by melt infiltration is a technique that initially uses the polymeric binder to join or glue powder feedstock in a layer-by-layer process to create intricate geometries and complex shapes [38]. A schematic of the

binder jet AM process is shown in Fig. 4a. After binding, AM parts with green strength are heated to release the polymer to leave spaces for subsequent melt infiltration. In this process, a lower temperature metal in the molten state wicks into a porous preform as a result of capillary forces [39]. When these processes are paired together, they offer two key advantages for the densification of rapidly-solidified powders. First, melt infiltration can densify preforms with centimeter-scale dimensions in a matter of seconds [40]. This means that in most cases of practical interest, melt infiltration requires only a brief thermal excursion that will not harm the microstructure and properties of the feedstock. Second, these processes yield net-shape objects [41]. Some of the advantages of binder jetting are that it is a cost-effective and low-energy method for fabricating parts from powdered media [42]. This is due to the lack of a laser in the system [37]. Also, the build volume of binder jetting machines is among the largest of any of the AM technologies [43]. One of the greatest advantages of this method is the ability to include very hard material in the soft metal matrix. Oak Ridge National Lab has led the binder jet AM of titanium carbide (TiC) and aluminum composite development (Fig. 4b) [44]. SEM image shows the dispersion of TiC powder in the Al matrix (Fig. 4b). Despite the numerous advantages of this process, it has some drawbacks. The main challenge with this process originates from the difficulty of predicting accuracy and tolerance due to part shrinkage during postprocessing steps [45]. A dedicated review paper has specifically highlighted concerns associated with the process and materials related to binder jetting [46]. Also, binder jetting parts may show poor mechanical properties due to internal porosity. This porosity can be reduced by sintering [47]. However, a significant challenge lies in reducing the surface roughness of the binder-jetted AM components involving soft metals and relatively hard phases. The presence of hard and soft phases makes it extremely challenging to formulate a scheme by which hard and soft phases can be smoothened simultaneously.



**Fig 4.** (a) Schematic diagram of Binder jet printing, (b) SEM of AM part produced by binder jetting involving TiC particle in Al matrix.

## 2. 4 Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is an AM method that uses a focused energy source, such as a plasma arc, laser, or electron beam, to melt a material that is simultaneously fed from the nozzle [48]. DED has been a process of choice for producing functionally graded complex high melting temperature alloys [49]. The benefits of DED include the capacity to control the bulk grain structure, which allows the process to be used for the repair of high-quality parts [50]. DED has adopted extremely high energy sources to melt virtually any metal and alloy [51]. Also, DED provides for the production of relatively large parts with minimal tooling [52]. One of this process's downsides is that DED may require significant postprocessing to achieve the desired surface properties. It is because of the reason that ~mm scale bands are present on DED-produced AM component surfaces [53]. It is almost impossible to use a DED AM part directly without getting rid of mm scale metallic ripples from the surface and achieving surface finishing to an acceptable level [53]. More intricate surface finishing challenges appear for the hidden surfaces or internal volumes on a complex-shaped DED AM component. Hence, the need for surface finishing is indispensable and may play a decisive role in adopting the DED AM component for the intended application [54]. The need of significant subtractive postprocessing can lead to sizable waste of materials [55]. Hence, one may tend to choose other AM alternatives such as selective laser sintering.

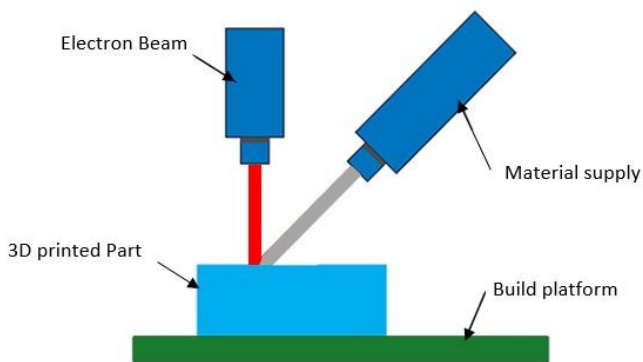
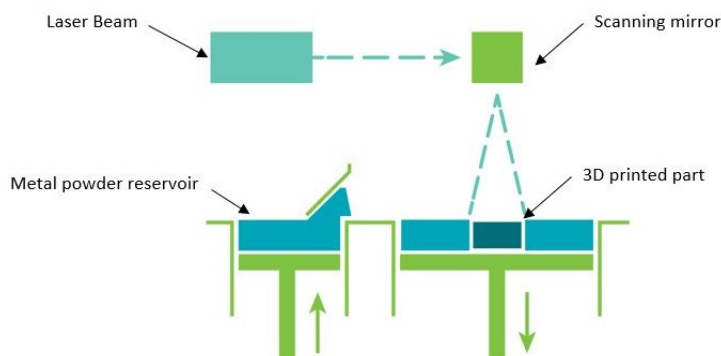


Fig 5. Schematic diagram of Directed Energy Deposition

## 2.5 Selective Laser Sintering (SLS)

Selective laser Sintering (SLS) is a process in which powder is used as raw material. SLS is the most popular AM system and represents the most significant part of metal AM production capabilities and industrial-scale experimentation for making deployable parts. SLS processes spread powdered material over the previously joined layer, ready for processing of the next layer. Each layer is then sequentially fused on top of each other. Then this particular powder melted together to form a solid object (Fig. 6). A very insightful review paper by Kruth et al. [56] has discussed the laser interaction with a wide range of materials and summarized that commonly considered Nd: YAG( $1.06\text{ }\mu\text{m}$ ) and CO<sub>2</sub> laser ( $10.6\text{ }\mu\text{m}$ ) are absorbed in different amounts in metallic and insulating powder and solid forms. Mazzoli [57] has published a review discussing the application of SLS in biomedical and mainly described laser interaction with non-metallic or polymeric materials. Walker et al. [58] have discussed the advanced topics related to laser material interaction and showed the realization of functionally graded material composition in laser powder bed fusion. This paper has provided insights into the SLS potential for complex components with spatially tailored properties and novel SLS machine technology addressing a combination of the significant challenges. For SLS printing, a wide range of raw materials is possible and has been optimized for the target application area. SLS has become the most dominant AM process because of its ability to produce functional components from common materials such as Thermoplastic, [59] Metal [60], Ceramic, and Glass [61].

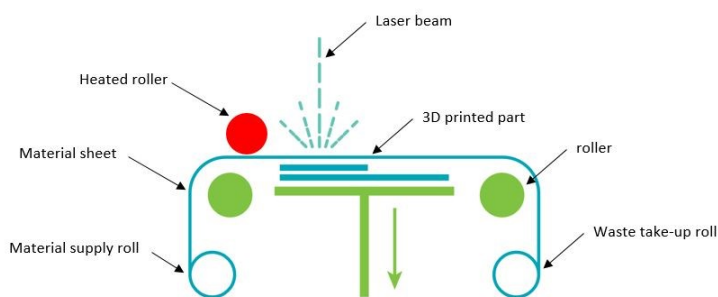
This method has several advantages. Among them are decreased material wastage and cost [62], the capability of building functionally graded parts [63], efficient recycling of unused powder, and good resolution compared to other additive manufacturing processes [64]. SLS is also capable of producing a wide range of metals and alloys. The SLS system also produced parts shown in Figure 1. Also, some SLS disadvantages include the cost of the machine being very expensive, a comparatively slow printing process [65], and parts having a grainy surface without any postprocessing [66][67]. Surface finishing is also an important concern for SLS AM components because of associated issues such as poor fatigue strength, corrosion, etc. [54]. The typical surface roughness of as-produced internal surfaces may be of the order of  $\sim 20\text{ }\mu\text{m}$  Ra due to partly fused  $\sim 30\text{--}50\text{ }\mu\text{m}$  sized raw powder material. Reducing internal surface roughness down to  $\sim 1\text{ }\mu\text{m}$  level is a significant challenge and topic of extensive surface finishing activities.



**Fig 6.** Schematic diagram of Selective Laser Sintering. Conceptual diagram adapted from Ref.[54].

## 2. 6 Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing (LOM) is an additive manufacturing process that is used to create 3D objects using paper, plastic, and metals [68]. The conceptual process flow is outlined in figure 7. In this process, the material is bonded in place over an existing layer using adhesives. The required shape is cut out through the use of a numerically guided laser. LOM has been considered a rapid prototyping technology, and its output was subjected to extensive characterization [69]. LOM has been viewed as a simple AM option [70]. The advantages of using LOM are quick and inexpensive manufacturing of large parts and no support material needed[71]. Among some limitations, breaking out parts is difficult. Surface finishing problem occurs on internal structures and undercut involving laminated layers and adhesives [72]. The surface finishing of LOM-produced AM parts will also need to focus on the composition and morphology of the primary material and bonding materials.

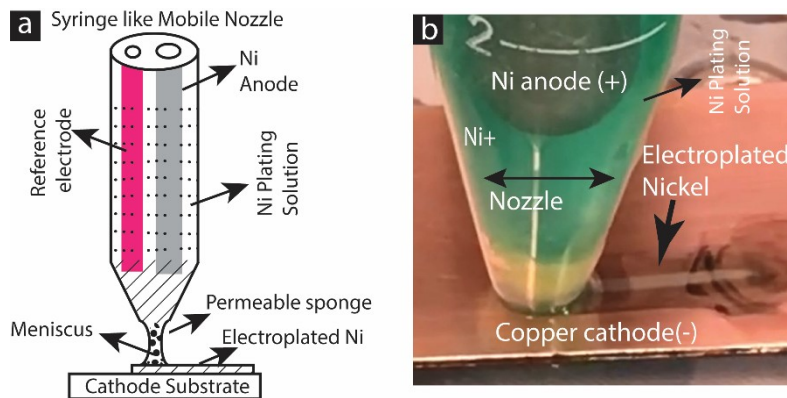


**Fig. 7.** Schematic diagram of Laminated Object Manufacturing. Schamatic drawing is based on process flow in Ref. [68]

## 2.7 Electrochemical Additive Manufacturing (ECAM):

A new class of metal additive manufacturing schemes has been designed based on electrochemical processes. It is noteworthy that electrochemical deposition is a classic process for creating thin films on conducting surfaces [54]. This process has been successfully attempted to produce micro-meso scale metal AM components [73]. In the last ~8 years, electrodeposition-based AM has been considered for near-room temperature metal manufacturing and has become a source of heightened interest [74]. ECAM has been attempted to print functionally graded complex NiCoFeCu alloys to demonstrate the potential of this field [75]. This method does not require high heating or laser melting for growing the build. Under this approach, atom-by-atom deposition occurs from the electrolyte containing the metallic ions. Our group has also started investigating electrochemical additive manufacturing based on our past expertise in electropolishing and electrodeposition. We have recently mimicked the tested concept described in the published literature [76]. For example, figure 8a shows a tubular structure filled with a nickel plating solution as the electrolyte, a nickel electrode that serves as an anode, and a reference electrode. A nozzle body contains an anode. The end of the tubular structure is tapered to form a nozzle with a permeable sponge (Fig. 8a). The role of the permeable sponge is to control the amount of electrolyte leaking through to create a meniscus on the top of a conducting surface (Cathode) [76]. As voltage is applied between the anode and cathode, the anode starts dissolving to replenish the plating solution with the metal ions. Ions start depositing on the cathode as the nozzle move. Here we show our preliminary work under which nickel is deposited on Cu as the nozzle travel laterally (Fig. 8b). In 2017, a room temperature desktop electrochemical 3d printer was demonstrated [76]. This is a promising approach to developing a novel set of materials by depositing multiple materials in the form of layers. Since electrochemistry can also be utilized to deposit semiconductors and polymers, hence a wide range of components with composite materials can be produced. Electrochemical AM brings peculiar advantages for producing components for energy harvesting where major emphasis is on the high surface area than physical strength [73]. This electrochemical AM approach is also demonstrated to produce graded material for electromagnetic applications [75]. Additionally, electrochemical AM is promising for enhancing the capabilities of components produced by SLS and other high-temperature processes by producing sensors [77]. ECAM-based sensors are quite significant and have been summarized in a recent review paper [78]. Electrochemical metal AM printing is

expected to produce a new set of challenges for surface finishing. The major disadvantage of the electrochemical AM is its slow manufacturing speed, which is the biggest hurdle [77]. It is also anticipated that large-scale AM components produced by the electrochemical route will possess high porosities and poor mechanical strengths. Surface finishing of the electrochemical AM components has not started yet, and we will have a better understanding as full-scale components evolve. However, one added advantage of this solution-based AM process is that liquid-based surface finishing, such as electropolishing and chempolishing, may be applied during the manufacturing process itself. With this concept surfaces that will be fully enclosed and sealed may be improved or enhanced during the electrochemical building processes.



**Fig 8.** Electrochemical additive manufacturing (ECAM) (a) process shown by schematic diagram adopted from [76] and (b) example of layered growth of nickel on copper substrate.

### 3. Current state of challenges and future directions of AM techniques

#### 3.1 Challenges of AM techniques

AM market in aerospace, medical, automotive industries, electronics, and consumer goods is expected to surpass the \$8 Billion mark by 2025 [79]. Although AM was first commercially utilized in the middle of the 1980s [80], this field still represents a small section of general manufacturing due to economic, safety, and technical considerations. According to recent research [81], only 21% of enterprise AM users utilize the technology for consumer goods and machine parts, whereas 63% use it for prototyping. This number makes it abundantly evident that we still have problems to solve before gaining wide adoption. We can generalize the challenges as technical, capability, financial, and design challenges [82]. Here we discuss some challenges specific to the metal additive manufacturing field and the surface finishing role in addressing these challenges as applicable.

##### 3.1.1 Technical and surface finishing challenge

Since metal AM is new compared to traditional manufacturing, there is much to learn and research. Materials for traditional manufacturing technologies have already undergone years of development in terms of both processability and the necessary product properties. In addition to this solid database of materials, the industry has defined material standards and specifications [83]. The main challenge comes from the acute dependency on the quality of raw materials and the type of metal AM adopted. Currently, metal AM considers the family of alloys based on aluminum, iron, titanium, cobalt, copper, and nickel. In the steel category itself, significant variations exist. For example, one needs to find the optimum quality of raw material in powder form for the powder bed-based laser sintering process. This challenge is so critical that main metal AM machine manufacturers have their own recommendations for the source of powder. Metal AM machine manufacturers generally provide assurance about the expected quality from the AM part when recommended powder manufacturer is utilized. Hence, a small variation in powder quality may complicate the process, and one needs to either re-optimize metal AM parameters or fix the raw material problem. Another associated problem is that the surface finish of the metal AM parts is extremely sensitive to the raw materials [84] and the selection of metal AM parameters such as inert gas environment [85], power, and building speed [86]. At present, no matter how well metal AM parameters are utilized or which manufacturing process is used, it is not possible to produce ready-to-use basic surface finishing, which is getting desired surface roughness. In addition, surface roughness can be significantly

different on external surfaces and internal surfaces. Generally, on the exterior surface of AM parts, a sandblasting or some primitive step is conducted to remove the loose or semi-fused particle from the surface and improve the appearance and roughness. However, internal surfaces may continue to have loosely connected semi-fused particles or process-induced surface roughness, no matter how shiny a metal AM part looks from the outside. Future work will address surface quality from multiple directions depending upon the consequences of poor surface roughness on internal and external surfaces. Future work will focus on designing a part based on the manufacturing process and the desired surface roughness and microstructure of the internal and external surfaces. The design of the metal AM part should also consider the possible postprocessing techniques for internal and external surfaces, which are discussed here. Until we set the standard and guidelines for a wide range of metal and alloys for AM, adopting metal AM in mainstream production will continue as a challenge.

### 3.1.2 AM Workforce Challenge

A successful transition to AM will need new engineering and management skills to exploit the full benefits of this technology. AM field is currently facing a significant skills gap and has been the motivation for initiating many targeted initiatives. Finding a professional and knowledgeable crew that can use an actual commercial-grade metal manufacturing machine is challenging. Most of the workforce lacks sufficient familiarity with the various materials and the demands of the design process to fully realize the potential of additive manufacturing. In addition, the metal AM manufacturing staff are expected to be knowledgeable about various complementary fields. For example, a staff operating a metal AM machine with the knowledge of metallurgy, mechanics of materials associated with different mechanical testing, and surface finishing techniques possible for getting desired roughness for intended application can provide precious input for the starting 3D model design. The future scope of workforce development may require multiple pieces of training and an organizational strategy to address the talent and training needs of AM field. In addition, the metal AM field is more demanding as one needs to consider the application in the areas such as aerospace, automotive, and biomedical implants, where the environment around parts may pose severe challenges and may lead to a direct impact on human health and life. To further advance the field of metal AM, there will be an additional need to know about various coatings and embedding sensors within the AM parts. Such scope of work will necessitate that future workforce or AM research employ personnel from a team of experts having knowledge of diverse fields, including semiconductor industries.

### 3.1.3 Financial Challenges

Most of the technology we use now was more expensive when it was first introduced [87]. This is due to the fact that more manufacturers will be attracted when technology is better understood. This contributes to the price of a particular technology being affordable. This trend holds for metal AM as well. However, due to the complex control and safety concerns, SLS AM machines continue to be of the order of million dollars mark. Additionally, service contracts are significantly costly for academic institutions and medium-scale industries and a common challenge. An educational institution or industry needs dedicated staff to safely operate and maintain SLS type of AM machine. The major players of today are those who have access to funding for R&D. Companies offer raw materials and services for a higher price to make a profit and cover costs. Also, each technique for metal additive manufacturing requires tight control over process parameters. This economic factor dramatically impacts the demand for extensive research by a wide range of institutions and researchers who can solve surface finishing for AM parts. The economic concern will continue to be difficult until a new AM breakthrough occurs. ECAM metal AM process, which is still in the developmental state, has a unique opportunity to produce novel forms of materials, including metals near room temperature. This process is expected to be very low and may become a desktop metal 3D printing option.

### 3.1.4 Design Challenge

Engineers continue to consider the same design limitations that make conventional manufacturing challenging. They return to tried-and-true, familiar design paradigms rather than adopting an altogether new approach, especially when it comes to engineers who may have spent most of their careers following a traditional set of procedures. Each design and production stage has a specific role in traditional manufacturing. Depending on each discipline's discrete function, the design is changed. In order to accommodate different design limitations, there are customized tasks and

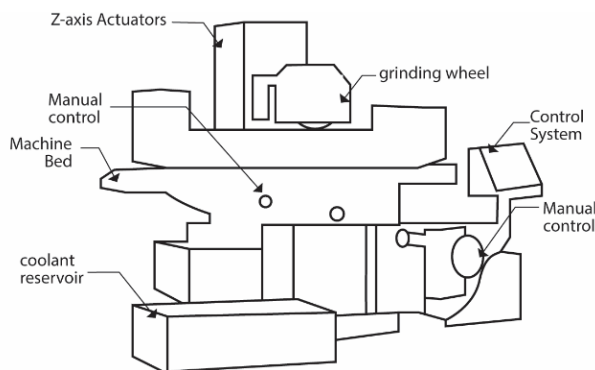
comprehensive design workflows for specific activities [88]. Designing of AM components is expected to involve AM process and post-processing challenges to built-in suitable tolerances up front.

### 3.2 Future Directions of AM techniques

Future industrial production will change significantly as a result of additive manufacturing. Additive manufacturing will cement its position as the manufacturing technology that will aid in the transition to a sustainable and resource-conserving society. AM will develop into a practical and affordable tool that can be used for the entire life cycle of a product, from concept models to aftermarket parts and everything in between. The future of metal AM will significantly depend on postprocessing techniques to ensure that surfaces can resist challenging environments and do not lead to the nucleation of defects during the life cycle. Postprocessing challenges have produced the opportunity to integrate sensors to monitor AM parts' health in challenging environments. Here we mainly review some key advancements in the field of surface finishing methods.

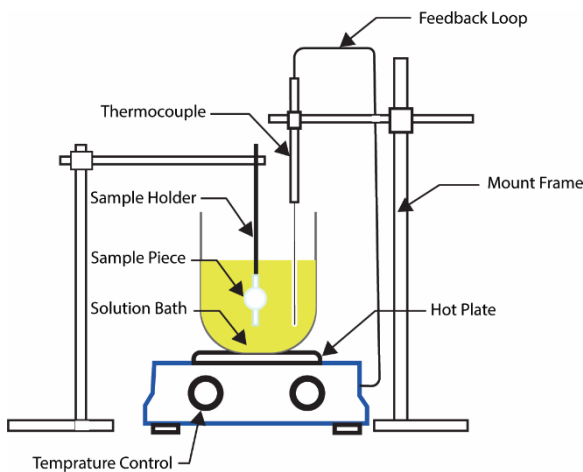
### 4. Review of Surface Finishing Technologies

Traditional surface finishing techniques such as turning, boring, drilling, milling, broaching, sawing, shaping, reaming, tapping, etc., are still used as a primary way of post-processing manufactured parts. The use of machining techniques, like grinding and cutting, on intricate AM components is challenging. Jiang et al. [89] investigated surface finishing on additively manufactured Ti-6Al-4 V alloy using precision grinding. They used a SMART N10 KOMBI, ELB-Schliff Werkzeug-180 Maschinen GmbH, Germany precision grinder, with a 300 mm diameter Cubic Boron Nitride (CBN) wheel for their study (Fig. 9). The machine has a position resolution of 0.1  $\mu\text{m}$  in X, Y, and Z direction. In the study, they reduced the as-built component surface roughness,  $R_a$ , by 91-94%. This is a substantial achievement but has some limitations. Precision grinding is not suitable for internal channels, heat exchangers, lattice structures, or non-flat complex 3D printed components (Fig. 9).

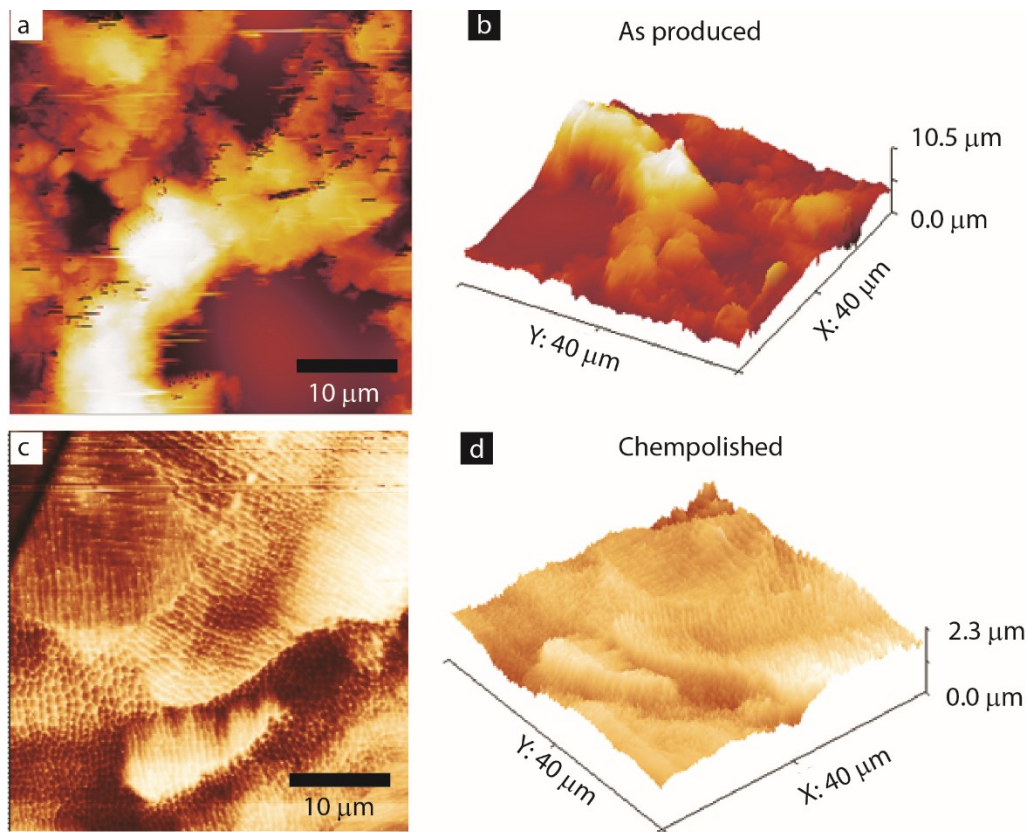


**Fig 9.** Schematic diagram of Precision grinder utilized for surface improvement on the accessible outer surface. Schematic based on Ref. [89].

Chemical polishing(chempolishing) is one of the most versatile alternatives used in recent research for the post-processing of additively manufactured components. Chempolishing is cost-effective, easy to apply, and effective for AM components of varying shapes (Fig. 10). Liquid chemical polishing solutions get to hard-to-reach surfaces of the AM parts, as shown in figure 11. Tyagi et al. [90] investigated chempolishing on additively manufactured 316 stainless steel. This process requires a simple setup that can monitor the temperature of the sample and solution closely (Fig. 10). This technique is based on the principle of oxidation and reduction. When the sample is immersed in the chemical polishing solution, the solution continually anodizes the surface and results in a bright polished sample. Interestingly, during chempolishing, bubble formation occurs on the surface and helps in removing the etching product from the surface. The bath used in this study was 10-30% phosphoric acid, 1-10% hydrochloric acid, 1-10% nitric acid, and 1-10% proprietary surfactants. A constant temperature of  $\sim 75^\circ\text{C}$  was maintained during the experiment. They were able to reduce the surface roughness,  $R_a$ , by 97% within 60 min using chemical reduction. The atomic force microscope data provide granular details of dramatic improvement on AM steel surface before and after chemical polishing (Fig. 11). The surface before etching was very uneven (Fig. 11a) and possessed random features of several tens of  $\mu\text{m}$  (Fig. 11b). After chempolishing AM surface started exhibiting micron-sized grains (Fig. 11c), and unevenness reduced significantly (Fig. 11d).



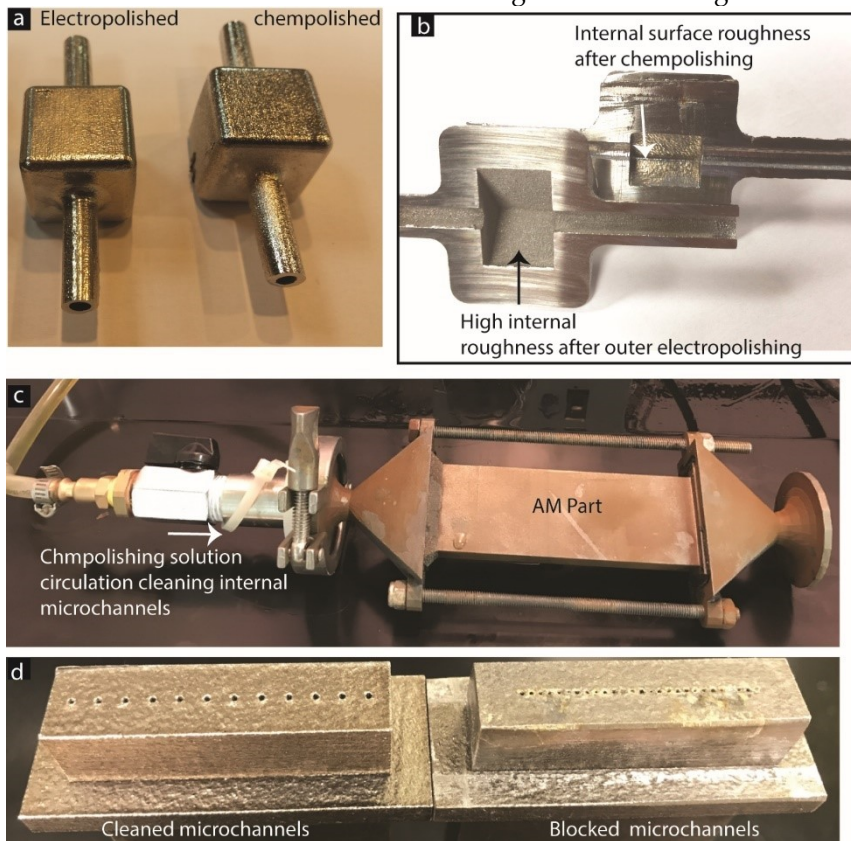
**Fig 10.** Experimental setup for Chempolishing process-based surface finishing.



**Fig 11.** Digital microscopic image of AM component before and after Chempolishing, (a) Before and (b) after

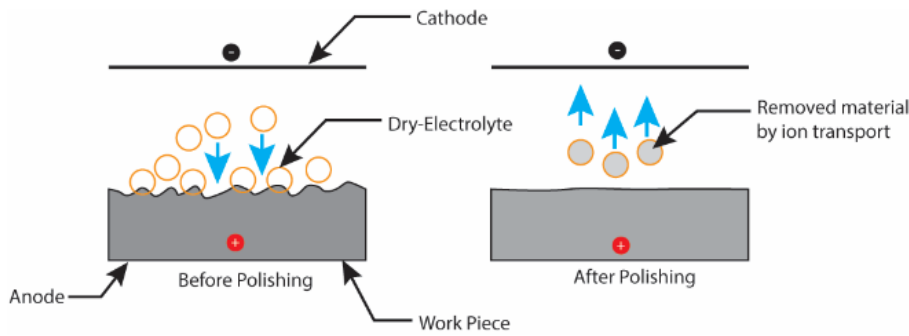
Chempolishing can become very useful for AM components where channel sizes are too small and too long to do electropolishing (Fig. 12a). Prior work demonstrated that ~ 2 mm diameter and 10 mm long channels allowed smooth chempolishing of the interior surfaces (Fig.12b). Electropolishing, another solution based method discussed elsewhere was completely ineffective (Fig. 12b). Chempolishing can be applied to AM parts with < 1mm diameter channels. One can custom-design fixtures to target the small channel in such a case to direct chempolishing solutions into channels (Fig. 12c). Pressurizing chempolishing solution may initially create a U-turn but will enable progressive chempolishing. Eventually, the chempolishing solution will start flowing through the channels by removing the internal blockage (Fig. 12d). AM heat exchanger with ~500 μm scale microchannels were subjected to chempolishing (Fig.12c). In as produced

state, channels in the AM sample were significantly blocked. Chemically dissolving the blockages by circulating chem-  
 polishing solution opened the channels (Fig. 12d). The ends of the heat exchanger's microchannels before and after  
 chempolishing of the internal channel were remarkably different (Fig. 12d). This work is still in its initial state, and a  
 detailed study about dimensional analysis will be included in dedicated publications in the future. In essence, this  
 chempolishing is akin to a micromachine that removes microscale materials to yield a highly smooth surface. The chem-  
 polishing-enabled internal surface finishing may also bring advantages over other liquid media-based surface finishing  
 approaches where some kind of abrasive media or suspended particles are used. Chempolishing limitation is that AM  
 parts must have inlet and exit points available to implement this process. Uninterrupted fluid dynamics may be critical  
 for microscale interior features in the making surface finishing successful.



**Fig 12.** Images of (a) external and (b) internal surfaces of AM components after electropolishing and chempolishing. (c) Experimental setup to circulate heated chempolishing solution through microchannels in AM heat exchanger. (d) Circulation of chempolishing cleaning microchannels; in the as-produced state, microchannels were irregular and blocked.

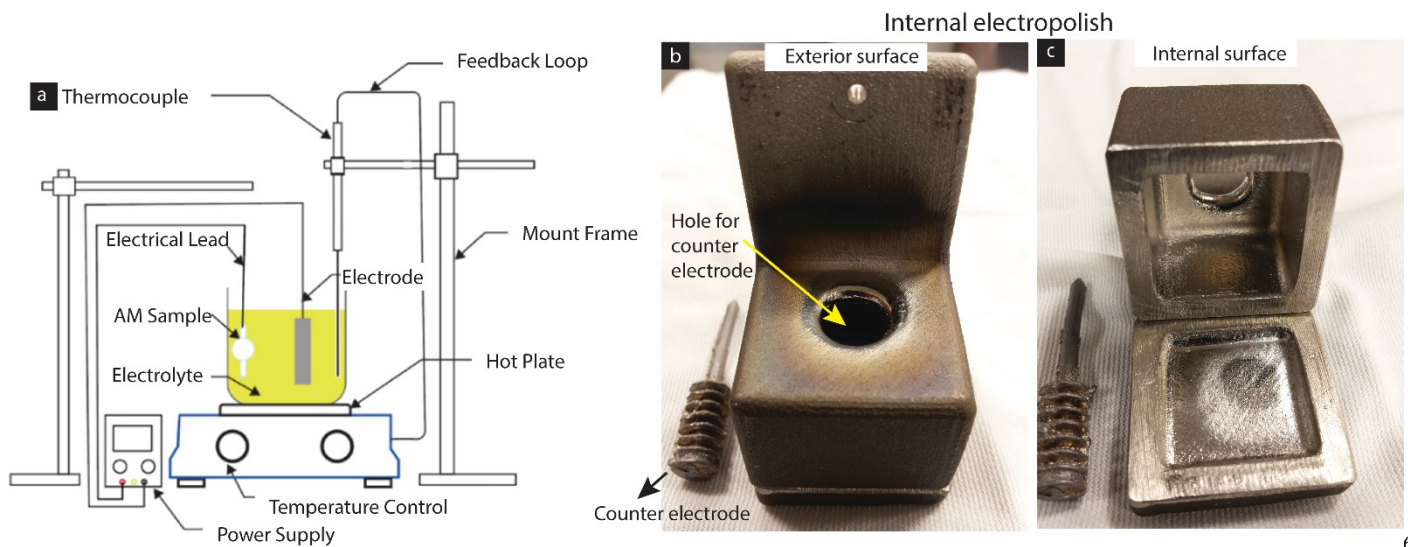
Han-Gil Woo et al. [91], applied a dry electropolishing technique on AM metal parts printed using Powder Bed Fusion (PBF) technology. This post-processing technique on additively manufactured components was recently developed by GPA Innova of Spain [92]. The fundamental principle of dry electropolish is similar to wet electropolish, where both use electric current to dissolve or transport ions from the metal surface into an electrolyte. However, rather than using a strong acid as a solution bath, the dry electropolishing uses spherical micro electro-powder made of resin (Fig. 13). This non-fluid electrolyte has a trace amount of acid on it. This method grinds and polishes metal using ion transport by using solid bodies. Han-Gil woo et al. [91] reported that the surface roughness  $R_a$  improved by up to 80% compared to as-built samples. The key limitation of dry electropolishing is difficulty in placing dry electrolytes in the internal channels of AM components. In the congested area surface, finishing products may also impede the surface improvement as dry electrolyte performance may reduce with changing the chemistry in its surrounding.



**Fig 13.** Conceptual mechanism of Dry Electropolishing process. Schematic based on Ref.91.

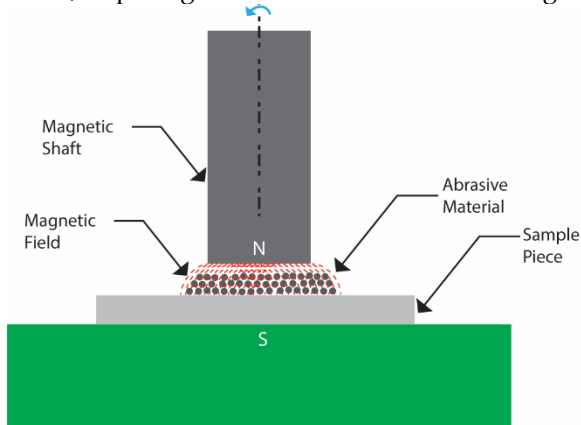
Several studies have investigated the application of liquid electrolyte electropolishing to AM components. It is noteworthy that electropolishing has been industrialized for surface finishing since the 1930s [93] and has vast potential to advance AM technologies. Tyagi's group analyzed the use of electropolishing on additively manufactured 316 stainless steel metals around 2014. This group was among the early adopters of this approach in the AM field [94]. The electropolishing process occurs via chemical and electric current action. The material removal is based on the anodic dissolution principle, in which polishing happens ion by ion from the workpiece anode. In the early stage of work, electropolishing utilized a ratio mixture of phosphoric and sulfuric acid as an electrolyte and a lead electrode (Fig. 14a). It is essential to have constant agitation, electrolyte temperature, and current density during the experiments. After 30 minutes of electrochemical reduction, the as-built component's surface roughness (Ra) reduced remarkably by >70%. It demonstrated that nearly ~200  $\mu\text{m}$  material removal from the surface of 316 stainless steel AM could significantly reduce the surface roughness [95]. It was observed that electropolishing could produce smoother surfaces as compared to the chempolished method. It is noteworthy that excessive electropolishing could bring the surface down to sub-micron Ra level. However, excessive chempolishing did not appear to significantly change the roughness level, which was typically >1  $\mu\text{m}$  Ra. Results are discussed separately for chempolishing [90] and electropolishing [95] for 316 stainless steel. Optical images showed a shinier outer surface on electropolished AM components (Fig. 12a); however, almost no improvement on the internal surface (Fig.12b). However, chempolishing was equally effective in reducing the surface roughness of the internal and external surfaces (Fig. 12b). The functionality of electropolishing could be further enhanced by custom designing the counter-electrode targeting the internal surfaces (Fig. 14b). According to our research one can perform electropolishing of internal surfaces as long as a suitable geometry counter electrode can be placed in the vicinity of internal surfaces. Here we show that an AM sample's interior surface became smooth and shiny after electropolishing (Fig. 14c). Electropolishing-based surface finishing is a topic of intense research and has been attempted in different forms. Tyagi group has also investigated the combined effect of chempolishing and electropolishing. Chempolishing and electropolishing were applied in different sequences, and the resulting roughness, physical, and chemical properties were studied [96].

Electropolishing has several limitations. Electropolishing is not applicable where it is impossible to bring the counter electrode and electrolyte close to the target AM surface. Additionally, excessive electropolishing has been found to remove the materials along the micro grains selectively and can make an AM part sensitive to failure. Hence, SEM and metallography are critical after the electropolishing to keep control of the microstructure. Electropolishing has another limitation about the difference in electrolyte and counter electrode requirements for different metals and alloys. Each metal and alloy may need a specific combination of acids, temperature, and counter electrode materials.



**Fig 14.** (a) Electropolishing set up. (b) SLS AM part designed for internal electropolishing to allow entering of custom designed counter electrode via 1 cm diameter hole; exterior surface remained unaffected when (c) internal surface improved significantly.

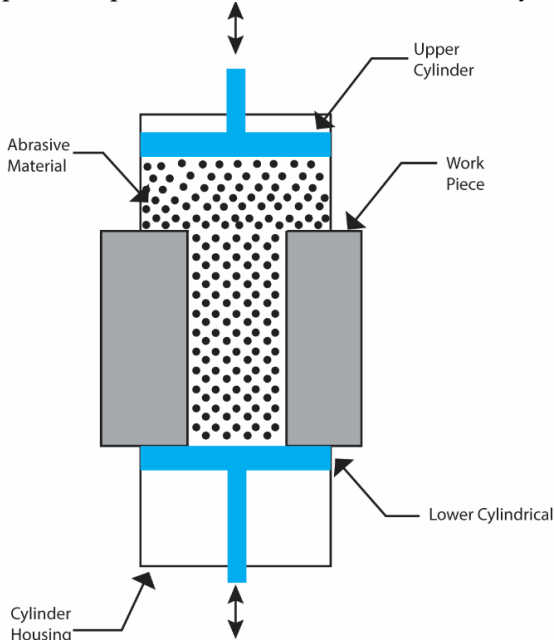
To further advance the surface finishing methodologies interesting mechanical abrasive process has been attempted. Magnetic abrasive surface finishing (MAF) is a non-conventional way of postprocessing metal and non-metal components. This surface finishing technique utilizes a magnetic field, ferromagnetic particles, and abrasive. This machining process can achieve a high-quality finish on the flat, curve, and internal channels. Hitomi Yamaguchi's [97] work implemented a magnetic abrasive surface finish on additively manufactured stainless steel parts (Fig. 15). The sample was a 25 mm disc with 12.7 mm thickness and an initial roughness value ( $R_z$ ) of 60-100  $\mu\text{m}$  before any postprocessing. Researchers changed the magnetic particle size and abrasive material type during the study. It is seen that magnetic abrasive finishing is easy to control the material removal rate and has excellent surface finishing capability. The characterization results show the roughness value goes down to 0.3  $\mu\text{m}$ , a 99.7% surface roughness reduction after a 200-polishing pass. The main limitation of the MAF is that it is challenging to apply to complex samples, especially with hidden surfaces. Additionally, magnetic metal and alloys may hinder the magnetic field profile required to conduct MAF, requiring additional efforts and investigations.



**Fig 15.** Magnetic abrasive surface finishing (MAF). The conceptual schematic is based on Ref. [97].

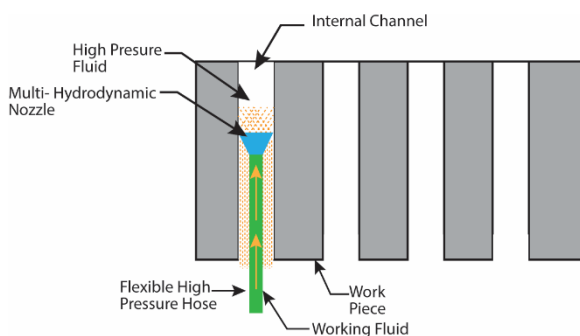
Abrasive surface finishing was attempted to improve the internal surface of AM components. For this target, attempts were made to use the abrasive flow machining (AFM) process for additively manufactured components. One of Kum et al. [98] work focused on material removal via abrasive flow machining on additively manufactured metal components. AFM uses a viscoelastic abrasive-laden media with high pressure through the internal channel. Typically, most AFM systems are driven by a piston (Fig. 16). Kum et al. [98] used a sample manufactured using a laser-based powder bed system. During the experiment, the abrasives moved at a rate of 500 mm/s and a pressure of 10 MPa inside the enclosed workpiece for 15 min. Results show outstanding surface finish and dimensional accuracy for AFM. However, there are some uniformity issues along the whole surface. The arithmetical mean height ( $R_a$ ) of the workpiece reduces

up to  $0.8\text{ }\mu\text{m}$ . Nevertheless, AFM showed that dimensional error was almost  $\sim 600\text{ }\mu\text{m}$  in some regions. Some of the key limitations of this method are that this process cannot be applied simultaneously to external and internal surfaces. Additionally, if some internal features are fragile, then the application of hydrostatic pressure during AFM can damage them. Also, channels and passages in AM parts have to be significantly bigger than the abrasive particle dimensions; else pressure profile will be nonuniform and may lead to undesirable nonuniformity in surface finishing.



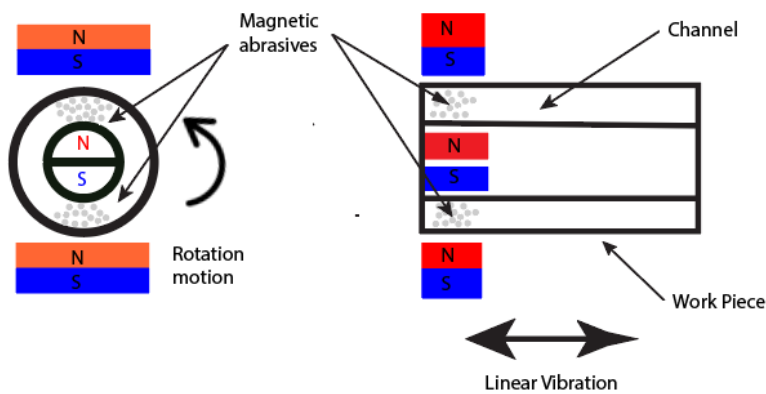
**Fig 16.** Abrasive flow machining (AFM) for internal surface finishing. The conceptual schematic is based on Ref. [98].

As additive manufacturing opens a new door for creative design, one can produce lightweight heat exchangers with excellent cooling capacity. Creative design in AM is highlighted best by the capability to manufacture complex internal geometries. Nagalingam et al.[99] investigated the multi-jet hydrodynamics approach on powder bed fused manufactured components. The focus of this study was surface smoothening the internal structure of parts with linear, stepped, and non-linear internal channels with various diameters. The study compared hydrodynamic abrasive finishing (HAF) and hydrodynamic cavitation abrasive finishing (HCAF) (Fig. 17). HAF and HCAF's main difference is that HAF is a pure slurry flow operation, while HCAF is a combination of slurry and cavitation flow. The surface finishing result is dependent on the internal structure and orientation of the internal geometries. Characterization shows both methods reduce the surface roughness of the interior surfaces. Statistically, the roughness is reduced 60-90% from the as-built sample, and final  $R_a \leq 1\text{ }\mu\text{m}$  and  $R_z \leq 20\text{ }\mu\text{m}$ . The limitation of this approach is that it will depend on the design of AM internal surface geometries. Some geometries involving twists and turns may not be treated with this method. Abrasive particle size may also limit the application of HAF and HCAF in improving narrow channels. This process and AFM can produce very different microstructures on internal surfaces compared to external surfaces. As a consequence, material testing strategies have to be reconfigured accordingly to identify particular failure mechanisms specific to internal and external surfaces.



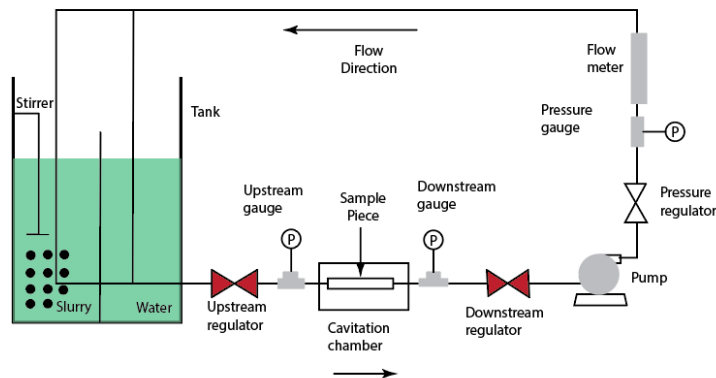
**Fig 17.** Hydrodynamic abrasive finishing (HAF). The conceptual schematic is based on Ref. [99].

Other researchers have started paying attention to surface finishing for internal surfaces. Guo et al. [100] propose a rotating-vibrating magnetic abrasive polishing method for the rough internal surfaces of AM components. This method was applied to a double-layered tube structure fabricated by selective laser melt (SLM) Inconel 718. the system allocates pair of magnets externally to the workpiece as well as a diametrically magnetized cylindrical magnet located at the center of the workpiece, along the axial direction. The magnetic abrasives were supplied to the gap between the outer and inner tubes. By moving the magnet in the transversal direction and rotating the workpiece, the magnetic abrasives continually polish the internal surface of the sample. It is seen that rough surfaces were uniformly removed from inner surfaces. Measurement of Arithmetical mean height  $R_a$  shows that roughness reduced from about  $\sim 7 \mu\text{m}$   $R_a$  to  $0.21 \mu\text{m}$ . The major disadvantage of using magnets around channels is that only limited internal surfaces can be improved. Additionally, variation in a magnetic field along the channels may lead to variation in the extent of surface finishing. Like MAF and HAF methods, the size of abrasive magnetic particles may limit the dimensions and shape of AM part channels.



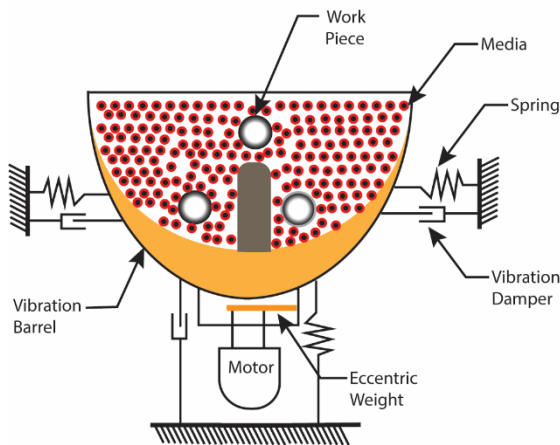
**Fig 18.** Schematic illustration of the rotating-vibrating magnetic abrasive polishing method. The conceptual schematic is based on Ref. [100].

AM components that consist of random roughness distribution throughout their surface is a key problem. A. Nagalingam et al. [101] investigate the possible use of hydrodynamic flow at its cavitating conditions along with freely suspended abrasive particles for finishing the internal surfaces of additive manufactured components. The system is a closed loop in which the fluid pump through the internal channel of AM part. The fluids contain entrained SiC particles within them. Cylindrical as-built aluminum alloy AlSi10Mg samples are used in experiments made with the Direct Metal Laser Sintering (DMLS) technique. For a specific study, the experiments were conducted at cavitation conditions with abrasive particles for  $\sim 5$  h. the result shows good improvement in surface finishing. From the topography characterization, the average surface roughness ( $S_a$ ) reduced from  $62.7 \mu\text{m}$  to  $44.1 \mu\text{m}$ . The disadvantage of cavitation-based surface finishing is that inlet and outlet are required to improve surface roughness; AM sample with one entry only cannot be treated. Similar to other pressurized flow-dependent approaches, this approach is unsuitable for AM parts with fragile internal features. Additionally, if a channel has interior features, then fluid dynamics around features will vary, leading to nonuniform surface finishing.



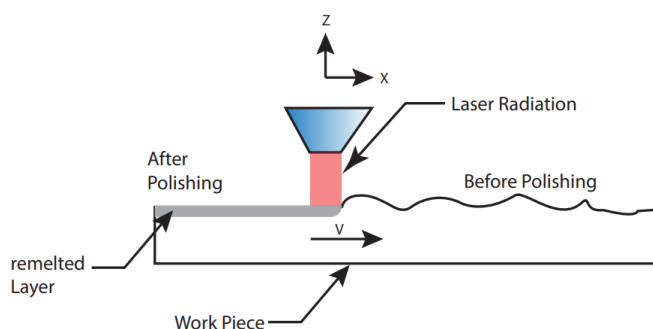
**Fig 19.** Hydrodynamic Cavitation Abrasive Finishing (HCAF) polishing method. Adopted from [101]

Atzeni et al.[102] used a Vibro-finishing process for samples produced using laser-powder bed fused technology. This finishing process uses ultrahigh vibration to rub the sample with abrasives. Vibro-finishing machines are available in a wide range of sizes and abrasive options (Fig. 20). The Vibro-finishing process is done in two steps. It starts with finishing and then is followed by polishing. In this study, two AlSi10Mg samples were subjected to finishing for 38 and 62 hours using FMX 3/8" TC abrasive. The polishing step is in FBC 50 medium with 1.5:100 dilutions in water and takes only two hours. The result shows a good improvement in surface roughness. The Sa value goes down from 44  $\mu\text{m}$  to 4  $\mu\text{m}$ . However, as a major Vibro-finishing may have attained dimensional inaccuracy on account of the high material removal rate. Also, instrumentation for the Vibro-finishing process is extensive and may not be suitable for a wide range of AM parts. This process is also ideal for external surfaces.



**Fig 20.** Vibro-finishing process. The conceptual schematic is based on Ref.[102].

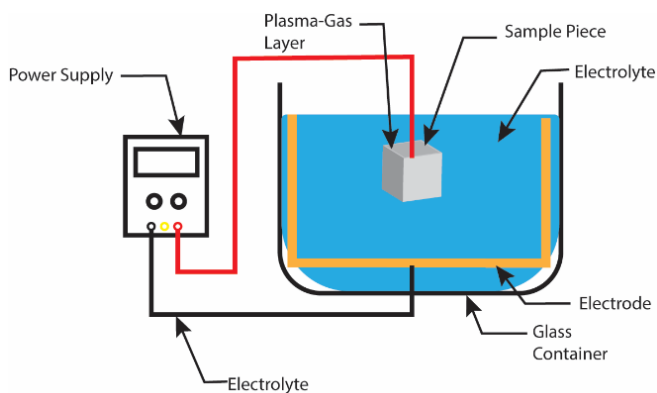
Laser machining has also been applied for surface finishing. Laser-based methods are advantageous for materials that are difficult for other surface finishing methodologies. The selective laser melting additive manufacturing process offers a wide range of materials for metal 3D printing. These materials include steel, copper, aluminum, and titanium. Titanium, for instance, is durable, tough, and corrosion-resistant. However, machining titanium is challenging due to its low thermal conductivity, and titanium is chemically very reactive with the cutting tool [103]. AM titanium alloys alleviate the challenge of machining pure titanium components. C.P. Ma et al. [104] demonstrated the possible use of fiber laser polishing on additively manufactured Ti-based alloys, such as Ti-6Al-4V (TC4) and Ti-6.5Al-3.5Mo-1.5Zr-0.3Si (TC11/BT9). A nanosecond pulsed fiber laser with a wavelength of 1060 nm, pulse duration of 220 ns, the repetition rate of 500 kHz, and spot size 44  $\mu\text{m}$  was used for the laser polishing (Fig. 21). Throughout the experiment, CP Ma et al. [104] investigated the roughness, microhardness, and wear resistance improvement. The results show surface roughness reduced from 5  $\mu\text{m}$  to less than 1  $\mu\text{m}$ . Microhardness increased by 10% compared to the as-built samples, and wear resistance in the laser polished sample improved up to 42%. The major disadvantage of laser polishing is that it increases manufacturing time significantly. Other more concerning matter is about laser machining applications on the side walls of complex geometries. Laser machining also dump additional energy and hence may become cause of mechanical deformation and warping of tenuous sections. Such machining can only be applied on the AM part during the manufacturing stage for best results; it is not applicable for the completed AM parts.



**Fig 21.** Fiber laser polishing. The conceptual schematic is based on Ref.[104].

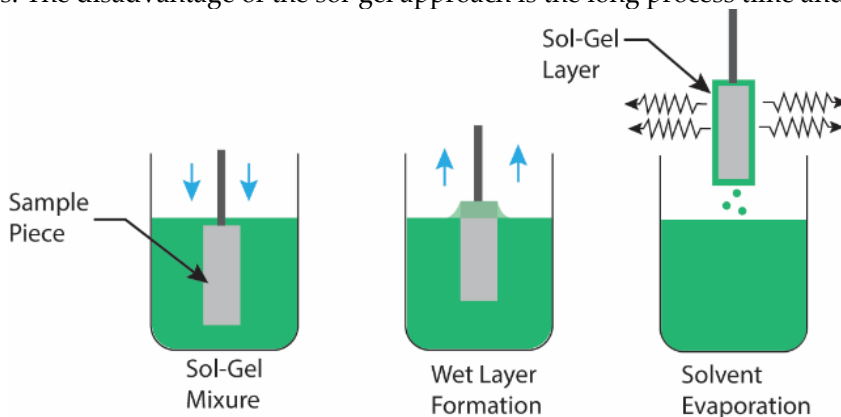
So far, we have looked at reductive surface finishing of AM parts, but the sample surface can also be improved by depositing material or coating the AM components. The coatings can improve the electrical, thermal, mechanical, or optical properties of the component. The deposition may be a chemical, electrochemical or physical process.

Recently, AM component surfaces were improved by growing native oxides. Plasma electrolytic polishing or plasma electrolytic oxidation (PEO) is an electrochemical process used for the surface finishing of AM components. PEO uses an environmentally friendly low aqueous concentration solution of salt and high applied voltage. This process can grow thick oxide layers (crystals) on the AM sample surface. After PEO, an AM part can achieve higher microhardness, corrosion resistance, and low roughness polishing. Aleksey B. Rogov [105] investigated the potential use of AC plasma electrolytic oxidation on AM and cast AlSi12 alloy substrates (Fig. 22). This method used a silicate alkaline bath as the electrolyte and alternate current. The results showed that the microhardness of the polished substrate was 3-5 times the microhardness of the as-built substrate. However, this study did not conduct a surface roughness or corrosion study. Hence, it is not clear if roughness increased or decreased after PEO. As a disadvantage, PEO cannot be applied to materials that do not form suitable quality oxides. The PEO-produced oxide layer may only serve a specific purpose and may be damaged in marine environments.



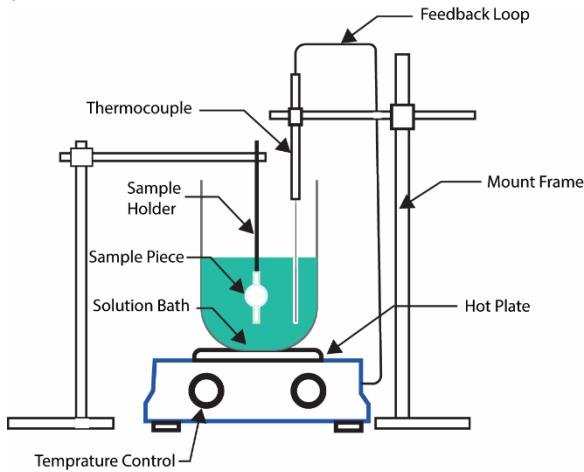
**Fig. 22.** Plasma electrolytic polishing. Adopted from process flow in Ref. [105].

Several thin film coating methods can enhance AM sample surface for a target application. Additive manufacturing is highly used to print custom orthodontic implants and prosthetics in biomedical engineering. Currently, it's not possible to use an as-built AM component due to several factors. The sol-gel functional coating reduces some AM surface limitations and provides substantial surface finishing potential [106]. Danish Technological Institute [107] published a report describing Sol-Gel coating as a promising alternative to improve the mechanical and physical properties of AM components (Fig. 23). The material they use for the specific study is aluminum 3003 alloy. The coating thickness is about 5-10  $\mu\text{m}$  and applied using a setup shown in Figure 23. Results show a considerable improvement in surface hardness. Sol-Gel coating has a pencil hardness of 5H (WolffWilborn) pencil hardness test. The main benefits of the sol-gel technique are a) easy fabrication, b) high uniformity of films, c) possibility of coating on substrates of any size and over large areas, and d) low processing temperature. Sol-gel has the ability to coat any geometry and complex shapes of AM parts. The disadvantage of the sol-gel approach is the long process time and high cost of raw materials [108].



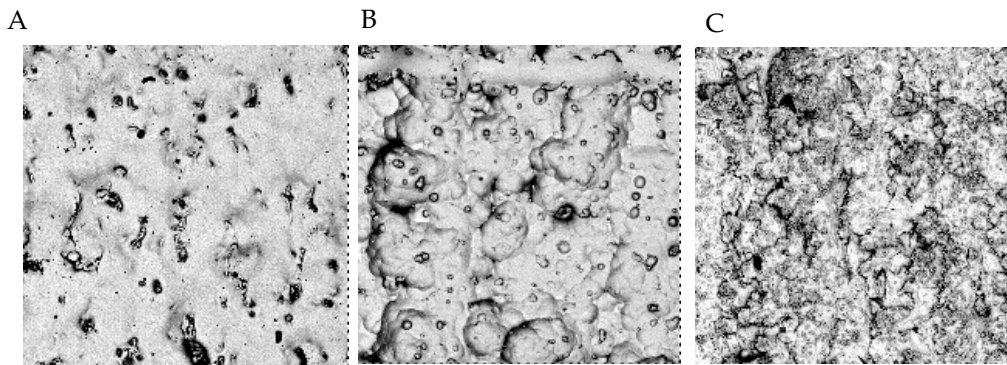
**Fig 23.** Sol-Gel (functional coating) coating on AM components. Adopted from process flow in Ref. [107].

The electroless coating is another highly promising method for protecting or enhancing the internal and external surfaces of the AM components. Diaz et al. [109] studied the effect of a Ni coating on an additively manufactured carbon steel part. Using the oxidation-reduction principle, they deposited nickel on the substrate immersed in an electroless solution without applying a current (Fig. 24). Results show electroless Ni plating increased hardness ~3 times. Also, the workpiece increases corrosion resistance for the coated metal with a noise resistance of 20 kΩ-cm<sup>2</sup> after 576 h of evaluation.



**Fig 24.** Electroless Ni plating of AM samples.

Recently, our group has also started the electroless Ni plating on AM steel components [110]. Nickel coatings are crucial for corrosion-sensitive AM components and have been in practice for a long time. Our preliminary studies show that the quality of coatings and morphology is a strong function of phosphorous content (Fig. 25). Other process parameters, such as AM samples' surface finishing before plating, are also critical factors. The application of electroless coatings on AM components is in its nascent stage. The major limitation of electroless coating is that it requires a surface activation step prior to electroless coating. Such activation processes are hard to complete in hidden areas or internal surfaces. Hence, even though electroless coating can produce conformal coating, it will not be of an optimum quality where activation steps do not occur.



**Fig 25.** SEM image for Electroless nickel plating (a) Low phosphorus (b) Mid phosphorus (c) high phosphorus Electroless Nickel Plating. The width of each figure is 100 μm [110].

## 5. Comparison of surface finishing technologies for additive manufacture components

It is observed that every surface finishing technique is dedicated to a specific research goal. In this paper, we like to generalize the comparison of all methods into two categories: external surface finishing (Table 1), and internal surface finishing (Table 2). One of the biggest challenges in comparing key results from various surface finishing papers is that different roughness and characteristic surface parameters are utilized. Here we have mainly focus on Ra, Sa, Sz and hardness for external surfaces (Table 1). For internal surface finishing, we compared Ra roughness parameter (Table 2). Based on the insights in Tables 1 and 2, one makes an informed decision. Let's assume someone's goal is to smooth the

external surface-specific part and the topology of the part is dominantly flat. In that case, the magnetic abrasive surface finishing technique produces outstanding surface finish capability with an arithmetical mean height Ra of 0.3  $\mu\text{m}$ . If a specific challenge arises from the convoluted internal surface and channels of AM components, chempolishing is a practical option. This is because the micromachining liquid solution work by itself; it starts to dissolve the rough surface with  $\sim 20 \mu\text{m}$  Ra. For the coating category of surface finishing, the goal of the specific surface finish is to increase the hardness of AM surface. Electroless Ni plating could be one of the best alternatives. The nickel ion in the electrolyte gives the surface superior surface hardness, measured in Vickers Hardness up to 457 HV.

**Table 1.** Comparison of surface finishing methods discussed.

| No | Method and Reference number                                   | Sample Material      | Ra~<br>$\mu\text{m}$ | Sz~<br>$\mu\text{m}$ | Sa~<br>$\mu\text{m}$ | Surface finish improvement | Hardness property                                                                |
|----|---------------------------------------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------------|----------------------------------------------------------------------------------|
| 1  | Precision grinding [89]                                       | Ti-6Al-4 V           | 0.65                 | N/A                  | N/A                  | 91-94%.                    | N/A                                                                              |
| 2  | Chemical polishing [90]                                       | 316 stainless steel  | 0.4                  | N/A                  | N/A                  | 97%                        | N/A                                                                              |
| 3  | Dry electropolishing [91]                                     | Inconel 718 meta     | 1.95                 | N/A                  | N/A                  | 80%                        | N/A                                                                              |
| 4  | Electropolishing [95]                                         | 316 stainless steel  | 0.39                 | N/A                  | 2.1                  | 70%                        | N/A                                                                              |
| 5  | Magnetic abrasive surface finishing [97]                      | 316L stainless steel | N/A                  | 0.3                  | N/A                  | 99.7                       | N/A                                                                              |
| 6  | Abrasive flow machining [98]                                  | Maraging Steel MS1   | 0.8                  | N/A                  | N/A                  | 90%                        | N/A                                                                              |
| 7  | Multi-jet Hydrodynamic abrasive finishing [99]                | Inconel 625          | 0.7                  | N/A                  | N/A                  | 60-90%                     | N/A                                                                              |
| 8  | Vibro-finishing process [102]                                 | Aluminum alloy       | N/A                  | N/A                  | 4                    | 90%                        | N/A                                                                              |
| 9  | Rotating-vibrating magnetic abrasive polishing [100]          | Inconel 718          | < 1                  | N/A                  | N/A                  | 92%                        | N/A                                                                              |
| 10 | Hydrodynamic cavitation erosion with abrasive particles [101] | AlSi10Mg             | 10                   | N/A                  | N/A                  | 40%                        | N/A                                                                              |
| 11 | Selective laser melting [104]                                 | Ti-6Al-4V            | $\leq 1$             | N/A                  | N/A                  | N/A                        | Surface microhardness of TC4 and TC11 increases about 32% and 42% consecutively. |
| 12 | Plasma electrolytic polishing [105]                           | AlSi12               | N/A                  | N/A                  | N/A                  | N/A                        | After polishing, microhardness improves 3-5 times.                               |
| 13 | Sol-Gel coating [106]                                         | Aluminum 3003 alloy  | N/A                  | N/A                  | N/A                  | N/A                        | The pencil hardness of 5H                                                        |
| 14 | Electroless Ni Plating [109]                                  | Carbon steel         | N/A                  | N/A                  | N/A                  | N/A                        | Increase in microhardness up to 457 HV.                                          |

**Table 2.** Comparison between internal surface finishing technologies.

| No | Method & Reference Number | Cross section area | Initial surface roughness Ra | Final surface roughness Ra |
|----|---------------------------|--------------------|------------------------------|----------------------------|
|----|---------------------------|--------------------|------------------------------|----------------------------|

|   |                                                               |                              |          |            |
|---|---------------------------------------------------------------|------------------------------|----------|------------|
| 1 | Multi-jet Hydro-dynamic abrasive finishing [99]               | 3.14 - 78.54 mm <sup>2</sup> | 4.5–7 µm | 0.5–1.0 µm |
| 2 | Chemical polishing [90]                                       | 4mm <sup>2</sup>             | 15 µm    | 0.4-µm     |
| 3 | Rotating-vibrating magnetic abrasive polishing [100]          | 275.67 mm <sup>2</sup>       | 7 µm     | < 1 µm     |
| 4 | Hydrodynamic cavitation erosion with abrasive particles [101] | 78.54 mm <sup>2</sup>        | 15–25 µm | ~10 µm     |
| 5 | Eelectropolishing [Authors unpublished work]                  | 75 mm <sup>2</sup>           | 10 µm    | ~1 µm      |

## 6. New Frontiers and Future Scope of Work

Postprocessing of AM parts is very comprehensive. At the current stage, surface finishing mainly encompasses the field of surface roughness reduction inside the interior areas and outer surfaces. This review is expected to provide a representative list of liquid-based surface roughness improvement methods for internal and external surfaces to empower metal AM practitioners to make well-informed decisions about suitable strategies. In a short span of nearly five years, the electropolishing method of liquid polishing has been attempted on AM components so often that it has been summarized in a dedicated review paper [111]. We recently investigated the impact of combining the strength of electropolishing and chemical polishing like liquid-based surface finishing approaches. We found that the results of combined treatment were better than the single-step electropolishing or chempolishing [96]. It is noteworthy that liquid-based surface finishing techniques have an added advantage because many traditional plating companies have the resources and technical knowledge to transform conventional electropolishing and chempolishing like classic processes for AM field. One successful example is REM Surface Engineering®, with >60 years' experience in plating. This company works on NASA-related AM components with a wide range of alloys and has developed several propriety iterations out of chemical and chemical-mechanical-based surface finishing approaches [112].

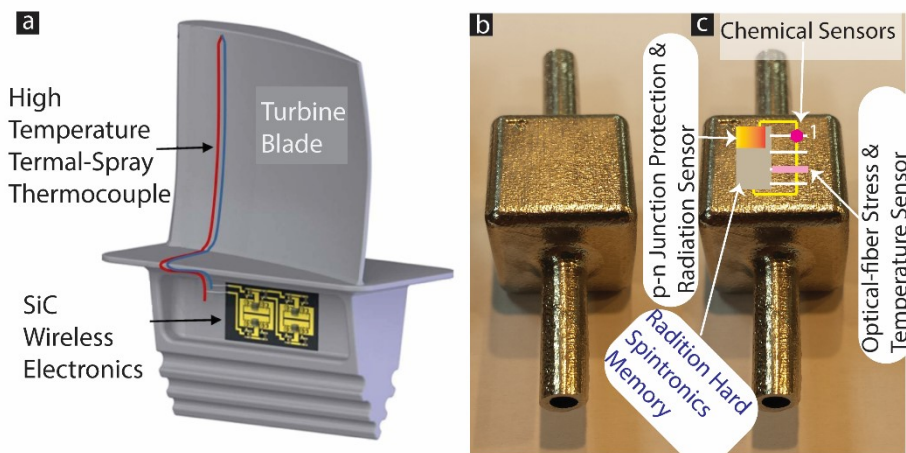
Testing the impact of AM surface finishing approaches on key properties like fatigue strength, corrosion, and microstructural properties necessitates collaboration between expert industries with academic institutions having the required resources and faculty expertise. There is a strong need to develop custom-designed surface roughness measurement techniques [113]. Surface roughness reduction techniques may produce different results in different directions on internal and external surfaces of AM components. It is because of the inherent difference in microstructural properties of AM components due to the impact of growth directions [114]. It will be challenging to measure the roughness of hidden surfaces and require a custom-designed solution for each AM component geometry. Figure 12b shows that AM components may have internal surfaces accessible through a sub-mm opening that is almost impossible to study with regular roughness measurement techniques such as profilometers and optical profilometers.

The new scope of surface finishing activities also includes applying various coatings on external and internal surfaces to advance the functionalities of AM components [110]. Given to uniqueness of AM component geometry for targeted application areas, a new frontier of research is evolving. The AM component-specific custom design coating process will be required to produce conformal coatings on interior and exterior surfaces. In our preliminary, we have found that electroless nickel coating processes are better qualified for the coatings of hidden surfaces that are otherwise not suitable for other processes like electrochemical plantings, physical vapor deposition, and chemical vapor deposition. The scope of work in the coating area of AM components coatings is by itself vast and form a new frontier of research.

The new frontier in AM research focuses on the challenging task of developing high strength self-monitoring component. Figure 27(a) shows an exemplary conceptual design of AM produced turbine blade with a stress monitoring wireless system [115]. AM-produced turbine blades will require specific custom design surface finishing to acquire promising surface quality for the integration of sensors suitable for harsh environments. AM field will significantly benefit from the micro-nanofabrication and semiconductor processing technologies for fabricating and packaging desired sensors on or within the AM surface. For example, silicon carbide-based p-n junctions can be used for sensing tasks in harsh environments. Also, thin film sensors are long known for engine applications [116], where AM parts can deploy. To advance this field, the AM workforce should also possess or acquire a background in device fabrication to develop successful solutions. To illustrate the scope of sensors on AM parts, here we show an example AM part with a hollow cavity (Fig. 27b). The internal surface of this AM sample is smoothed by chempolishing. But external surface

is further smoothened by the application of electropolishing to reach sub- $\mu\text{m}$  roughness to allow suitable surface preparation for sensor integration. Limited work is accomplished in this area. Here, we show a conceptual overlay of multiple sensors on the surface of AM hollow chamber (Fig. 27c). This AM component will be able to monitor temperature, radiation, and chemical environment and locally store the data in radiation hard memory for periodic and authorized retrieval.

Smart additive manufacturing is another exciting future direction. This direction of research not only continues to improve popular powder bed-based laser sintering and direct energy deposition methods but will also encompass science and technologies of other methods such as low-temperature electrochemical additive manufacturing (ECAM) and binder jet additive manufacturing (BJAM) (Fig. 4b). It is critical to note that future AM parts are to be developed keeping a myriad consideration such as strengthening process, surface finishing, sensor integration in the intended environment. For this complex task, the application of artificial intelligence (AI) will be indispensable. AM field will also evolve by keeping up with the progress in advanced materials suitable for different postprocessing requirements.



**Fig. 26** (a) Conceptual image of a wireless sensor mounted on AM turbine blade. (b) AM hollow part surface finished by liquid-based processes. (c) Conceptual overlay of different sensors on the surface of AM component.

**7. Conclusions:** This paper aimed to provide a general understanding of the post-processing of AM components while shining lights on new frontiers. The conclusions are the following.

1. Surface finishing of AM components is the bottleneck issue that is limiting the application of innovatively designed components in the intended environment. As an example, a corrosive environment and cyclic loading will lead to premature failure of AM with poor surface finishing.
2. The scope of surface finishing in the AM field is much more than simple roughness reduction. AM surface finishing will include innovative technologies for producing desired coatings for application in chemically harsh and high-temperature environments.
3. 21<sup>st</sup> Century AM components can be designed and produced by adding compatible sensors to monitor the health of the components and integrated system. Such smart AM components can be produced by advanced surface finishing technologies involving the integration of sensors doing live monitoring of threat situations such as temperature, stress, and chemical environment.
4. Presently surface finishing is focused on improving the surface roughness on internal and external surfaces of AM components. In this paper, we discussed several AM technologies and highlighted the specific surface-associated challenges and their advantages and disadvantages based on our experience and understanding of the literature.
5. Selective laser sintering (SLS) has become a significantly mature and desirable AM process due to the extensive research and development in process control for manufacturing components with a wide range of metals and alloys. Most of the surface finishing research is focused on SLS-based AM components. The challenge of surface finishing will change with AM process. The low-temperature electrochemical AM process has strong potential to produce innovative functional components with metal or hybrid materials that will produce a different set of surface finishing challenges.

6. Liquid-based micromachining is almost essential for AM surface finishing, especially for complex geometries and hidden internal surfaces. Electropolishing and chemical polishing are highly mature conventional surface finishing methods that are being reinvented to serve the AM field. Several iterations of liquid-based machining are discussed in this paper. 692-695
7. Coating-based surface finishing will require strategies to coat the AM components' external and internal surfaces uniformly. Electroless and sol-gel are promising methods for AM field. Coating-based surface finishing is critical for components produced via binder jetting-based AM that involves multiple hard and soft phases, e.g., Titanium nitride in the aluminum matrix. Such parts are hard to improve by machining methods but may improve via coatings. 696-700

#### Declarations: 701

**Conflicts of Interest:** The authors have no competing interests to declare that are relevant to the content of this article. 702-703

**Author Contributions:** Pawan Tyagi had the idea of the review paper. Wondwosen did a literature search and critical review. The review paper was written by Wondwosen and critically reviewed by Pawan Tyagi. Wondwosen completed conceptual illustrations and literature review. Experimental data for chempolishing and electropolishing was provided by Pawan Tyagi. Lucas Rice provided samples for the experimental study. 704-707

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**Data Availability Statement:** Data included in this paper is available upon reasonable request. 713

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