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Study on Polishing Technologies for Additive Manufacturing Parts

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ABSTRACT

Additive manufacturing has a good application prospect in aerospace, medical implantation and other fields, but the molding surface quality is poor, without post processing can not meet the requirements of high service, polishing processing is a key link in the high-performance metal additive manufacturing technology chain. This paper summarizes the characteristics of the ladder effect, the high roughness of the forming surface. In recent years, additive manufacturing technology, also known as 3D printing, has been highly valued by aviation enterprises for its unique advantage in rapid prototyping, particularly for complex metal parts. However, due to the layer-by-layer growing process of 3D printing, the built parts often have poor surface roughness and are not suitable for practical use without post-treatment. Based on this foundation, the primary focus of research in the field of additive manufacturing for metal parts polishing includes electrochemical, laser, and abrasive flow polishing technologies. The progress in these areas is examined with consideration given to various manufacturing processes, different types of metal powder materials, and diverse structures (such as porous structure and high aspect flow channels) found in additive manufacturing samples. This review summarizes the research findings related to surface roughness, material removal, surface residual stress, profile accuracy retention, and other technical indicators associated with the polishing process for additive manufacturing metal parts. Finally, the paper discusses potential future developments in polishing technology for 3D printed metal parts.

Keywords: Additive manufacturing; molding surface; electrochemical polishing; laser polishing; abrasive flow machining

INTRODUCTION

Additive manufacturing is also known as “3D printing”, by converting three-dimensional digital molds into a series of two-dimensional models, using “layered manufacturing, layer by layer” directly to grow solid parts. The connotation of additive manufacturing continues to deepen, in recent years, with the technological breakthroughs such as powder materials, its application has been expanded from functional prototype parts manufacturing to industrial parts manufacturing, of which metal powder as raw material metal additive manufacturing is the most typical. Metal additive manufacturing technology is divided into two categories: selective melting technology characterized by powder cladding (PBF) and directed energy deposition (DED) technology characterized by directed powder delivery(Khalid et al. 2023).Additive manufacturing technology based on powder cladding includes various techniques such as selective laser sintering (SLS), direct metal laser sintering (DMLS), selective laser melting (SLM), electron beam melting (EBM), and so on. Based on directed energy deposition, there are laser melting deposition technology (LMD) and laser near-net forming technology (LENS) (Łyczkowska et al. 2014).

Compared with traditional additive manufacturing, The benefits of metal additive manufacturing are evident in the following aspects: First, the freedom of design. Additive manufacturing enables the direct manufacturing of complex structural parts optimized for the purpose of lightweight structure and optimal function (such as heat dissipation); The second is structural integration, the degree of structural integration of additive manufacturing parts is high, and the quantity of assembled parts has been significantly decreased.The third is on-demand customization, the use of additive manufacturing can be small batch, multi-variety manufacturing, to meet the demand for customization. At present, metal additive manufacturing is extensively utilized in the aerospace and medical implant industries(Sudhakara et al. 2020; Q. Wang et al. 2021).

In the aerospace field, the aeroengine LEAP-1B adopts additive manufacturing method to manufacture nickel-cobalt alloy fuel nozzles (Cheng et al. 2019), which reduces the production cycle by 2/3 and the production cost by 50% (Figure 1a). The GEnx aero engine 8-stage low pressure turbine blades are made of titanium alloy blades using EBM technology, reducing the mass by 20% (Figure 1b). The Ariane 6 rocket uses additive manufacturing to achieve integrated manufacturing of In718 alloy fuel nozzles, reducing 248 components to one, reducing cost by 50% and reducing delivery time by 80% (Figure 1c) (Hu et al. 2024).

In the field of medical implantation, additive manufacturing can produce porous implants that match the mechanical properties of host bone, avoiding the phenomenon of “stress shielding” induced by traditional solid implants(Habeeb et al. 2023), and better promoting the growth of surrounding bone tissue (FIG. 2a). The open porous structural scaffold formed by additive manufacturing technology has better biocompatibility due to its internal pores being connected through each other (Figure 2b)(S. Han et al. 2020a).

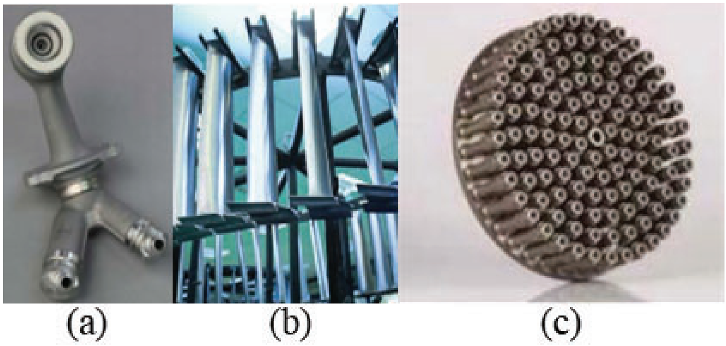

FIGURE 1. Applications of metal AM parts in aerospace industries: (a) aeroengine fuel nozzle, (b) blades, (c) rocket fuel nozzle
Source: Hu et al. (2024)

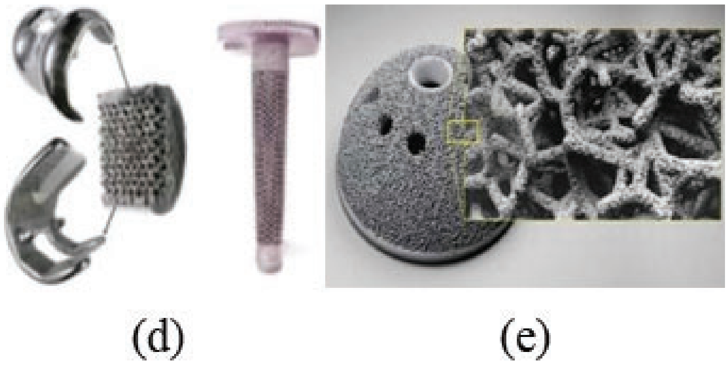

FIGURE 2. Applications of metal AM parts in medical implants: (d) knee implant, (e) acetabular cup
Source: S. Han et al. (2020b)

At present, the mechanical properties of additive metal parts are better than those of traditional parts, for example, the mechanical properties are better than castings(Sudhakara et al. 2020). However, the existence of a large number of pores inside the metal parts of additive manufacturing and the substandard quality of the as-built surface are still significant defects of this technology(Khorasani et al. 2020; Yan et al. 2021). The forming surface of additive manufacturing metal parts is in a rough surface state. For example, the surface roughness Ra of SLM forming parts is between 10 and 50**μ**m, while the traditional machining can reach Ra=2.5 **μ**m or less(Ryan et al. 2021). Therefore, in the metal additive manufacturing flow chart shown in Figure 3, the parts must be "post-processed" after printing, using heat treatment technology such as hot isostatic pressing (HIP) to reduce the internal pores of the parts, reduce the residual tensile stress, and carry out post-treatment polishing to remove the surface defects of the parts and improve the surface quality. Additive metal parts must be polished to meet the service requirements. Polishing is the last key process to guarantee the properties of metal parts in additive manufacturing, and the morphological characteristics and causes of forming surface are the basis of polishing.

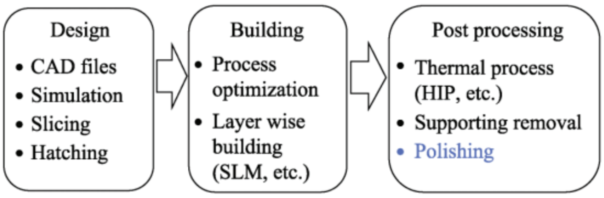

FIGURE 3. Flowchart of AM proces

CHARACTERISTICS AND CAUSES OF ADDITIVE MANUFACTURING MOLDING SURFACE

The "staircase effect", "balling effect" and "powder adhesion" The main factors leading to the poor surface quality of metal parts formed by additive manufacturing are inherent in the process itself.

STAIRCASE EFFECT

Additive manufacturing, with its characteristic of 'layered manufacturing, layer by layer superposition' as depicted in Figure 4, results in a stepped contour on the surface of the molded part that may not perfectly match the CAD model. This 'staircase effect' leads to roughness on both internal and external surfaces of additive manufacturing parts, particularly on tilted surfaces and curved sections of the suspension.

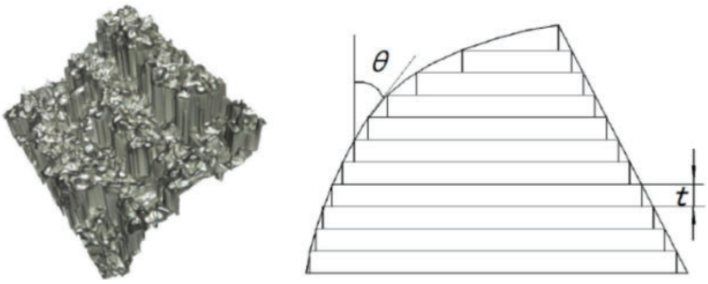

FIGURE 4. Staircase effect

BALLING EFFECT

During the growth of components, rapid increase in the surface tension of the molten material leads to instability, causing it to burst into several smaller melts and reach a new thermal equilibrium. After solidification, these smaller melts form spherical particles that adhere to the surface of the component, as depicted in Figure 5. This "spheroidization effect" also results in poor surface roughness(Li et al. 2024).

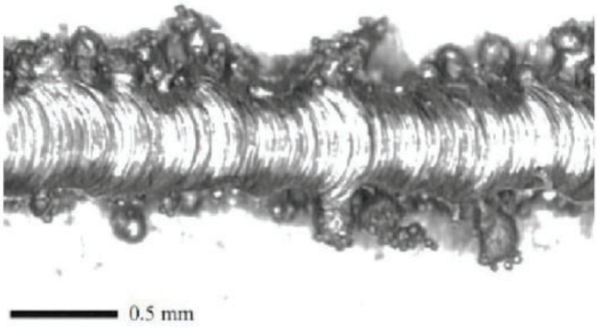

FIGURE 5. Balling effect
Source: Li et al. (2024)

POWDER ADHESION

The metal powder is not adequately melted in the heat affected zone, leading to the powder adhering to the surface of the part, as illustrated in Figure 6. Following multi-layer forming, un-melted powder particles will aggregate and bond, resulting in a rough surface on the parts(L. Wang et al. 2023). Furthermore, unlike the uniform and regular surface morphology achieved through milling, additive manufacturing's continuous fusion laps will eventually create an up-and-down ripple morphology. Due to the combined effects of "step effect", "spheroidization effect", "powder adhesion" and weld bonding, the surface morphology of additive metal parts exhibits non-periodic characteristics(Khorasani et al. 2020; Urlea & Brailovski, 2017; L. Wang et al. 2023).

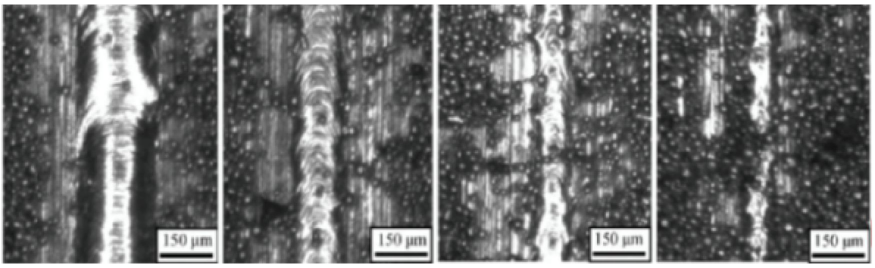

FIGURE 6. Powder adhesion

In summary, The surface quality of metal parts produced through additive manufacturing is subpar, and it fails to meet the high serviceability requirements without subsequent polishing treatment. Polishing is a key link in the additive manufacturing technology chain. At the same time, the characteristics of additive manufacturing complex structural parts have strong interference and poor processing accessibility of small cavity runner, leading to problems such as difficult to guarantee the quality of subsequent polishing processing, which is one of the shortcomings of high-performance additive manufacturing at present. Currently, extensive research has been conducted both domestically and internationally on the post-treatment polishing of metal parts produced through additive manufacturing(Khalid et al. 2023). It has important research significance and application value to study the polishing method of additive manufacturing metal parts and realize the machining of additive manufacturing metal parts with low cost, high efficiency and quality consistency.

RESEARCH PROGRESS OF ADDITIVE MANUFACTURING PARTS POLISHING

There are four ways to improve the forming surface quality of additive manufacturing metal parts: improving the quality of metal powder, optimizing the stacking forming direction, optimizing the forming process of additive manufacturing (laser or ion beam power, scanning speed, scanning spacing, slicing strategy, temperature control, etc.), and post-treatment finishing(Mughal et al. 2022). Through the first three ways to improve additive manufacturing technology, it is still unable to solve the problem of poor surface quality of parts(Bugvi, Mughal, Jamil, Kazim, Shabbir, Shahid, Dar, Asif, et al. 2024). From the perspective of technology and manufacturing cost, additive manufacturing parts polishing is indispensable.

Additive manufacturing metal parts are still widely used by hand polishing. However, the quality of manual polishing depends on the operator’s level of experience. Its consistency is poor, and the cost of labor and time is high. Additionally, the dust generated in the polishing process can be harmful to human health. Sandblasting and CNC grinding and polishing have limited accessibility for processing complex inner curved structures and porous structures, and are generally used for cleaning and polishing the outer surface and removing the oxide layer. Electrochemical polishing technology, laser polishing technology and abrasive flow polishing technology have good processing accessibility, and are widely used in the polishing of additive manufacturing metal parts. Table 1 shows the polishing effects of different types of additive manufacturing metal parts.

TABLE 1. Comparison of polishing methods for additive manufacturing parts

Polishing methods	Materials	AM methods	Roughness/μm
CP/ECP	Ti alloys(Dong et al. 2019)	SLM,	*Ra* 6~12 to
	SS316L(Chang et al. 2019)	DLMS	*Ra* 0.2~1
		SLM	*Ra* 8 to *Ra* 0.18
Laser polishing	Ti alloys (Khorasani et al. 2020)	SLM	*Ra* 12.3 to *Ra* 0.9
	IN718 (Fang, 2020)	SLM	*Ra* 7.5 to *Ra* 0.1
	SS316L(Bhaduri et al. 2017)	DM	*Sa* 2.4 to *Sa* 0.25
AFM	TC4(Peng et al. 2018)	SLM	*Ra* 14 to *Ra* 1.6
	Ti alloys(Peng et al. 2024)	SLM	*Ra* 12~15 to *Ra* 0.51

CHEMICAL POLISHING AND ELECTROCHEMICAL POLISHING

Chemical polishing (CP) and electrochemical polishing (ECP) are widely used in the surface treatment of difficult-to-process metal parts, and the treatment has remarkable effects in removing spheroidized particles and adhesive powders from the inner surface of open porous mesh structures. In order to effectively reduce stress shielding and promote cell differentiation and tissue growth around the implant, the medical implant of additive manufacturing is generally formed by combining a dense layer and a porous layer, as shown in Figure 2. However, the mesh structure forming the porous layer has a small aperture, and the strut of the mesh is weakly rigid, and the surface adheres to the spheroidized layer and powder particles which are easy to fall off. How to improve the static and anti-fatigue properties of this kind of grid structure is the difficulty of polishing.

By using a polishing liquid containing hydrofluoric acid and nitric acid, the SLM formed porous sample was chemically polished by Łyczkowska et al (2014). The research showed that magnetic stirring was helpful to ensure the stability of the chemical polishing process. Pyka et al (2013) polished the additive porous sample by combining chemical polishing with electrochemical polishing. After polishing, the strut surface roughness Ra decreased from 6-12μm before polishing to 0.2-1μm. Dong et al (2019) used chemical polishing and electrochemical polishing methods to polish the Ti-6Al-4V mesh structure formed by DLMS, and studied the surface roughness and profile changes of strut(Dong et al. 2019).Due to the low conductivity of the electrolyte, local overcorrosion can occur, resulting in a less effective electrochemical polishing on the internal surface compared to the external surface. In general, chemical polishing can effectively remove the metal powder particles adhering to the surface of the wire column and eliminate the crack initiation point, and electrochemical polishing can further reduce the surface roughness on this basis in order to achieve the objective of enhancing the mechanical properties of the grid structure.

Electrochemical polishing of metal parts with initial roughness Ra of about 1μm has a remarkable polishing effect, which can reach the mirror level. However, the surface roughness Ra of additive manufacturing parts is significantly higher than 1μm(Habibzadeh et al. 2014), and the selective material removal in different areas cannot be guaranteed by electrochemical methods, resulting in serious oversize of parts after polishing(Chang et al. 2019). Chang et al (2019) proposed the strategy of combining Overpotential ECP (OECP) and electrochemical polishing (ECP) to try to solve this problem, and its principle is shown in Figure 9. In the first step, the overpotential electrochemical polishing is utilized for the removal of surface irregularities caused by the step effect and spheroidization effect.,and the surface with gentle profile changes is processed. The second step is to use electrochemical polishing to process a flat surface with low roughness. For SLM forming 316L stainless steel sample, its electrochemical polarization curve is shown in Figure 10. The voltage range corresponding to the platform current

(1.5-1.9V) is the voltage operating range in the electrochemical polishing process, and the corresponding overpotential chemical polishing (OECP) voltage operating range is 2.0-2.1V. After polishing the 316L stainless steel mesh sample, the roughness Ra was reduced from the initial 8μm to 0.18μm, the material removal thickness was about 70μm, and the profile remained good.

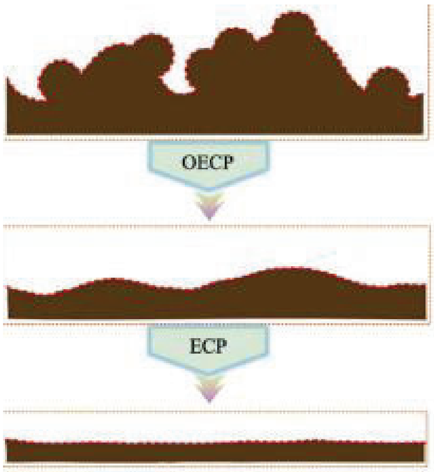

FIGURE 9. Polishing strategy with combination of CP and ECP
Source: Chang et al. (2019)

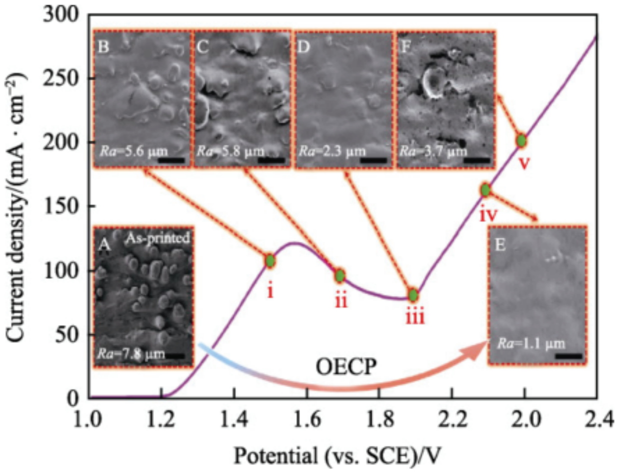

FIGURE 10. Polarization curve for the 316L sample from SLM process

Source: Chang et al. (2019)

The growth direction of additive manufacturing parts also has significant influence on the electrochemical polishing effect. Urlea & Brailovski (2017) used SLM to shape V-shaped Ti-6Al-4V sample to study the material removal of parts with different built orientation during electrochemical polishing(Urlea & Brailovski 2017). Under the set test conditions, the material removal amount of the sample with a growth direction angle of 0°was 0.12 mm, the material removal amount of the sample with a growth direction angle of 45°~90° was 0.16~0.20 mm, and the material removal amount of the sample with a growth direction angle of 135° was 0.28 mm. Therefore, in the process of electrochemical polishing, the profile change amplitude of different parts in different growth directions is different, which should be included in the scope of tolerance design of additive manufacturing parts.

LASER POLISHING TECHNOLOGY

As shown in Figure 11, the laser polishing principle uses the laser beam thermal effect to form a molten pool on the surface of the workpiece, and uses the surface tension and gravity of the molten pool to drive the liquid metal flow, and then quickly condenses to obtain a smoother surface. Laser polishing is non-contact processing. For different metal surfaces, by controlling the output energy and frequency of the laser, the laser polishing layer thickness can be controlled at the micron level(Bugvi et al. 2024).

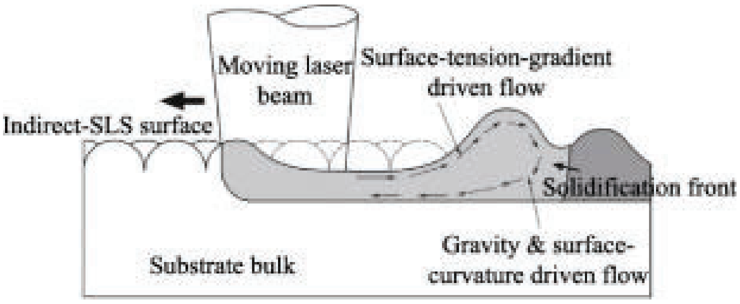

FIGURE 11. Principle of laser polishing
Source: Bugvi et al. (2024)

Ukar et al. (2010) studied the polishing effect of laser polishing on horizontal and inclined structure of SLS formed parts(Jailan & Jaafar, 1999). Rosa et al. studied the polishing effect of laser polishing on thin-walled curved parts. Bugvi, Mughal, Jamil, Kazim, Shabbir, Shahid, Dar, Musa, et al (2024) laser polished the sample of additive manufacturing TC4 titanium alloy after sandblasting(Peng et al. 2024). After polishing, the roughness Ra decreased from 12.3µm to 0.9µm, but the corrosion potential of the sample moved forward, the surface corrosion resistance decreased, and residual tensile stress existed in the polishing layer. Bhaduri et al (2017) utilized an additive to create a SS316L stainless steel sample for investigating the surface morphology of the workpiece following laser polishing. The surface roughness Sa was reduced from 2.4µm to 0.25µm.After undergoing laser polishing, the surface texture of the workpiece became isotropic., and the roughness values measured along different directions were very close(Bhaduri et al. 2017).

Fang (2020) used SLM to form the IN718 plate sample and studied the changes in the morphology, microstructure and hardness of the polishing layer after laser polishing(W. Han & Fang, 2019). After laser polishing, the surface roughness Ra of the workpiece decreased from 7.5µm to less than 0.1µm, and the microhardness increased from 345HV to about 440HV. The thickness of the polishing layer is about 120µm, and the cross section of the polished sample is shown in Figure 12. Figure.12a shows that the polishing layer and the substrate have completely different micromorphologies, indicating that the chemical components in the polishing layer have significantly changed. The partial magnification diagram shown in Figure 12b shows that the interlayer lap marks generated by SLM forming in the polishing layer have completely disappeared. The X-ray diffraction (XRD) results of the samples before and after polishing are shown in Figure 13. Compared with the initial surface, the peak value of the laser polished surface (111) phase decreases, but the peak value of the (200) phase and (220) phase increases, which indicates that the surface of the workpiece in the process of rapid melting, accompanied by grain refinement, γ “phase deposition leads to changes in the microstructure of the laser polished layer, which has a different microstructure from the matrix.

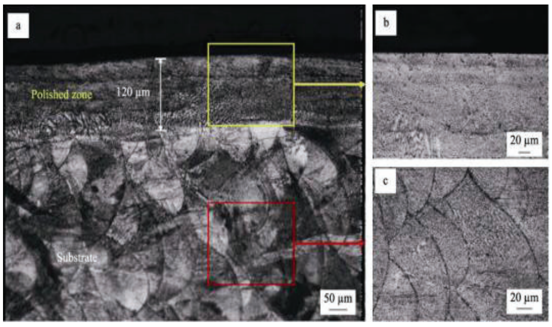

FIGURE 12. Cross section of polished IN718 sample from SLM process
Source: W. Han & Fang (2019)

The wettability of the polished surface is also a key point of laser polishing research(Kubiak et al. 2011). Yung et al (2018) conducted a study on the impact of laser polishing parameters on surface wettability by fabricating flat samples of cobalt-chromium alloy (CoCr) using selective laser melting (SLM) .The machining parameters, such as the beam defocusing distance and beam energy, have a significant influence on the wettability of the polished surface of the plate sample.

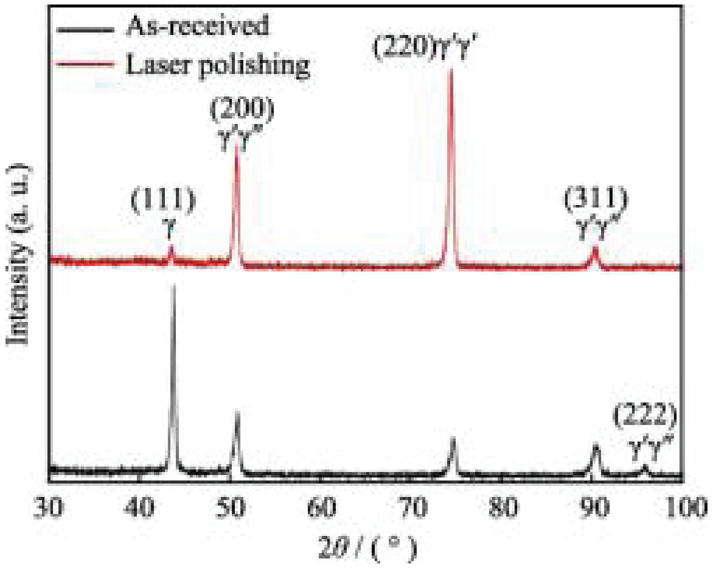

FIGURE 13. Testing results of XRD for the IN718 sample from SLM
Source: Kubiak et al. (2011)

ABRASIVE FLOW MACHINING TECHNOLOGY

When the viscoelastic Abrasive medium is driven by hydraulic pressure, it flows reciprocally on the workpiece surface through the flow channel formed between the fixture and the workpiece surface, carries out minor removal of the processed surface material, and realizes processing such as eliminating flash, guiding circle and polishing(Q. Wang et al. 2021). Abrasive flow machining has high machining accessibility, and has obvious advantages for polishing of complex internal cavity structure and complex internal flow channel(Q. Wang et al. 2021).

Khorasani et al (2020) were the first to utilize abrasive flow technology for polishing additive manufacturing parts and eliminating the stepped morphology of the formed surface(Bugvia et al. 2021). Uhlmann et al (2015) adopted abrasive flow polishing of SLM shaped blade sample, but there was still a problem of "overthrowing" at the inlet and exhaust edge of the blade(Uhlmann et al. 2015). Duval-Chaneac et al(2018) conducted a study on the impact of abrasive flow machining on the hardness and residual stress of additive manufacturing samples(Duval-Chaneac et al. 2018). After polishing, the surface hardness increased from 35.5HRC to 55.5HRC, and the surface residual compressive stress amplitude reached more than 400 MPa. S. Han et al. (2020) studied the effects of abrasive particle size, scratch width of polished surface, ploughing and rolling action on residual compressive stress of surface layer(W. Han & Fang, 2019). Bremerstein et al(2015) studied the influence of abrasive passivation on polishing effect and found that the material removal amount and polished surface quality decreased by about 30% and 20% after abrasive passivation(Bremerstein et al. 2015).

Dalian University of Technology has been engaged in research on abrasive flow machining for many years, and has developed abrasive flow machining equipment and serial abrasive media. On this basis, abrasive flow machining of various additive manufacturing metal parts has been studied, and the changing laws of parts' surface morphology, material removal and surface residual stress during material removal have been explored(Wei et al. 2019). In this paper, SLM was used to form aluminum alloy grille workpiece, and the evolution of surface morphology during grille flow machining with group holes was studied. After polishing, the workpiece surface roughness Ra decreased from 14 μm to 0.51 μm, and the micro-convex peaks caused by spheroidization and powder adhesion were removed by abrasive flow polishing.

Chemical polishing and electrochemical polishing through chemical reaction, electrochemical reaction to achieve polishing processing, with outstanding processing accessibility and no mechanical force required for operation., so poor processing accessibility of weak rigid complex structural parts of the internal surface, such as medical implant mesh porous structure, with good processing effect. However, chemical polishing and electrochemical polishing solutions generally use acidic solutions, and environmental protection emissions need to be solved.

Laser polishing offers several advantages, including high flexibility, non-contact polishing, high energy density, and environmental friendliness. However, the current laser polishing technology is unable to polish the internal surface of complex parts, in addition, the more expensive equipment and operating costs of laser polishing are also problems that need to be solved.

Abrasive flow machining has high machining accessibility, and has obvious advantages for complex cavity structure and complex internal flow path polishing. However, in the process of abrasive flow polishing, the surface pressure of the abrasive medium on the workpiece is at MPa level, and the problem of how to achieve the internal surface polishing of thin-wall and low-stiffness structural parts needs to be solved.

CONCLUSION

This paper introduces the electrochemical, laser, and abrasive flow additive manufacturing polishing technology for metal parts. The research work on roughness, material removal and surface residual stress is summarized and analyzed. The aforementioned research has made significant advancements in the mechanism of material removal, machining for low roughness surfaces, and the creation of functional surfaces (such as hardness and wettability).

Metal additive manufacturing currently has a strong development momentum, compared with the progress of parts growth process related technologies, the development of additive manufacturing metal parts post-processing polishing technology is relatively slow, may become the bottleneck in the metal additive manufacturing technology chain. Based on the research of the polishing mechanism of the formed surface of additive manufacturing, a quantitative data system for analyzing the relationship between process parameters and polishing indexes was established for the polishing of metal parts of additive manufacturing through the analysis of the polishing quality of the formed surface and the changes in the profile of the parts, and the technical requirements for precision polishing of metal parts of additive manufacturing were established. It provides reference and constraint conditions for metal additive manufacturing design and part growth optimization, which is of great significance to open up the technology chain of metal additive manufacturing.

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DECLARATION OF COMPETING INTEREST

None.

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