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# A review: finishing technologies of parts made by metal powder-bed additive manufacturing

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**Abstract:** Metal powder-bed additive manufacturing (AM) is known to possess good application prospects in the aerospace, medical and other fields. However, the furnishing of the surface quality of the AM parts is poor, and post-processing is required to meet the high applicability. The finishing process is the main link in post-processing for high-performance AM parts. In this report, the applications of machining, laser polishing, chemical and electrochemical polishing, abrasive flow machining and other typical finishing techniques used in the finishing of metal powder-bed AM parts are reviewed. Additionally, the evolution of surface roughness, material removal and residual stress of workpieces with different materials, different manufacturing processes (SLM, EBM, etc.) and different structural forms during the finishing process were analysed. An efficient and precise finishing technology can obviously improve the surface quality of the AM metal parts, which can be of great significance for the diverse applications of AM parts and reduce the costs.

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**Keywords:** finishing technologies; additive manufacturing; metal parts; powder-bed.

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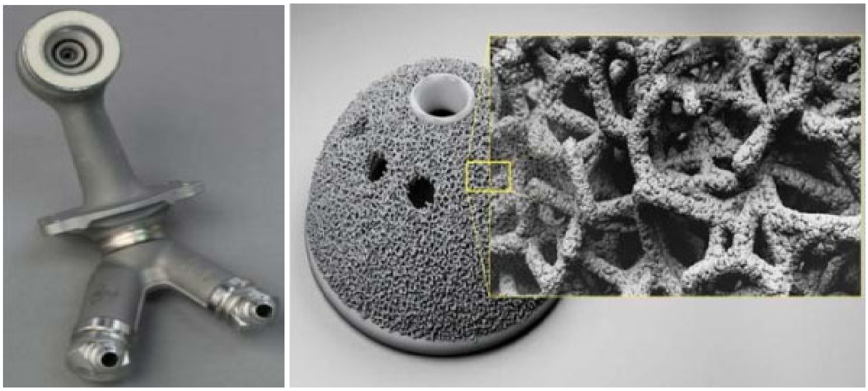
## 1 Introduction

Powder-bed AM technologies mainly include the selective laser melting (SLM), selective laser sintering (SLS), electron beam melting (EBM), etc. (Wu et al., 2018; Galati et al., 2019; Calignano et al., 2017). Although the efficiency of formation of the powder-bed AM is low and the size of the parts is limited, it can manufacture high precision parts with complex shapes (complex shapes and complex internal cavities). As a result, it is widely used in the field of aerospace, medical implants and automobile sectors (Frazier, 2014; Wang et al., 2020a). For example, in the aerospace field, the AM method is adopted to manufacture the nickel-cobalt alloy fuel nozzles [as shown in Figure 1(a)] for the aero-engine LEAP-1B, which can shorten the production cycle by 2/3rd and reduce the production cost by 50%. In the field of medical implantation, AM lead to formation of the porous implants [as shown in Figure 1(b)] that match the host's bone-mechanical properties, avoid the 'stress shielding' phenomenon caused by traditional solid implants, and promote the growth of the surrounding bone tissue (Wang et al., 2020b). Currently, the metal AM technology is applied to a variety of materials, including stainless steel, tool steel, titanium alloy, nickel-base superalloy, cobalt-based superalloy, low-expansion nickel-iron alloy, ceramic-based hard materials and metal compounds (Biamino et al., 2011; Beese and Carroll, 2016; Wang et al., 2017).

AM can partially replace the application of traditional manufacturing technology, and has a very broad application prospect. However, although there are many advantages over traditional machining techniques, an obvious limitation of AM is that the surface integrity of the last layers of manufactured parts is poor (usually 1–20 μm from the top surface) (Safdar et al., 2012), which is mainly related to AM principle, equipment precision, and process parameters, among which the step effect, spheroidisation effect and powder adhesion related to the AM manufacturing principle are the main factors leading to the poor surface quality of metal parts made by AM (Malekipour and El-Mounayri, 2018). For example, the surface roughness of SLM formed parts is 10~50 μm Ra, while the surface roughness of parts made by conventional mechanical processing is lower than 2.5 μm Ra (Hascoët et al., 2019). The metal AM processes require a finishing process, such as machining, grinding or polishing, to remove rough, porous and defective surfaces for AM parts to function (Bordin et al., 2017; Jinoop et al., 2019).

In order to improve the surface quality of the parts produced by different AM processes, a variety of secondary machining techniques have been applied, such as cutting, mechanical polishing, abrasive flow machining (AFM), chemical polishing (CP), electrochemical polishing (ECP) and laser heat treatment, etc. This review mainly analyses and evaluates the experiment and application of the finishing technology of metal parts made by powder-bed melting AM, so as to provide guidance in the improvement of the surface quality of AM metal parts.

**Figure 1** Application of AM technology, (a) fuel nozzle (b) acetabular cup implants (see online version for colours)



(a) (b)

*Source:* Wang et al. (2020b)

## 2 Finishing technology

### *2.1 Mechanical processing*

Several drawbacks of the metal AM include the poor surface finish and poor accuracy that seriously hinder its wider applications, since most mechanical and aerospace applications require closer part tolerances and 'mirror' surface finish. The related problems can be solved by cutting, grinding and polishing in the mechanical processing (Zhu et al., 2013). Mechanical processing is an important means to improve the quality of the parts, besides also has a strong processing adaptability. However, the materials of AM parts are generally difficult to process in the traditional machining, such as titanium alloy, superalloy and stainless steel. With the complex structural characteristics, it is not easy to carry out the post-processing machining of AM parts (Li et al., 2018; Salonitis et al., 2016). Therefore, it is necessary to study the machinability mechanism of AM parts.

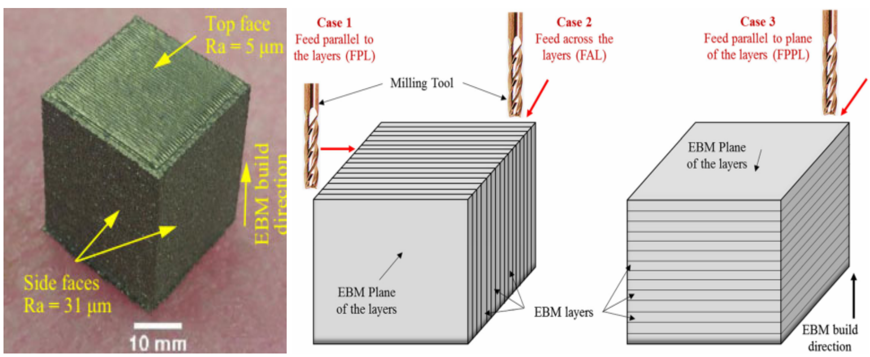
The semi-finish turning experiments of EBM Ti6Al4V alloy under dry and liquid nitrogen cryogenic conditions were carried out by Umbrello et al. (2017). It was found that the thickness of the $\alpha$ layer in the surface microstructure of the parts machined under cryogenic conditions was always smaller than that of the parts machined under dry conditions, thereby resulting in a higher surface microhardness. Rotella et al. carried out the semi-finish dry turning experiments of Ti6Al4V parts made by EBM, direct metal laser sintering (DMLS) and conventional forging. The cutting speed employed was 50, 80 and 110 m/min, the feed rate was 0.2 mm/rev, and the cutting depth was 0.2 mm. It was found that with the increase in the cutting speed, the surface roughness Ra of the parts decreased (the variation range is 1.9~1.3 μm), and the Ra value of forged parts was smallest and that of DMLS was the largest. The thickness and microhardness of the modified layer on the machined surface increased with an increase in the cutting speed, and that of EBM was the largest (Rotella et al., 2018). Bertolini et al. studied the key problems of the surface integrity evaluation of EBM Ti6Al4V alloy after cutting at three different feed rates under the conditions of dry, coolant and low temperature. The samples machined at low temperature showed a deeper influence layer, which provided a thicker and more compression hardening layer. The feed rate exhibited a great influence on the residual stress. At a higher feed rate, the number of surface defects increased and the surface became rougher, regardless of the cooling conditions and processing route (Bertolini et al., 2019). Umbrello et al. and Bertolini et al. proved the advantages of cryogenic technology in the processing AM Ti6Al4V alloy parts through comprehensive comparison of machined surface integrity.

Coz et al. used SLM technology to fabricate a thin-walled cylinder of Ti6Al4V with 20 mm internal mesh structure and 1.5 mm external skin. Then dry precision turning experiments of the part using uncoated carbide tool with various cutting angles and tool nose radius were carried out under different cutting parameters. It was found that the precision cutting condition led to minor cutting forces (about 8N), which were not enough to cause the geometric deviation of the thin-walled cylinder. Feed rate and cutting depth showed a significant effect on the surface hardness of the workpiece. Micro defects of ploughing and plastic deformation appeared on the surface. The residual stress was the compressive stress determined by the tool geometry, and there was no metamorphic layer on the sub surface. Precision cutting produced SLM Ti6Al4V with high precision and surface quality, which had a little effect on surface integrity (Coz et al., 2020).

Anwar et al. (2018) used $\gamma$-TiAl powder with an average size of 110 μm and EBM technology to fabricate 25 × 25 × 25 mm titanium alloy cube, and used the optimised process parameters to add the materials from bottom to top, perpendicular to the substrate to manufacture parts. Upper surface roughness of the parts was 5 μm Ra, and side roughness was 31 μm Ra. The parts prepared by AM process exhibited highly anisotropic characteristics (Guo et al., 2017; Buchanan et al., 2017). The step effect, spheroidising effect and powder adhesion in the manufacturing process led to an inconsistency in the morphology and roughness between the top surface and side surface. Therefore, it was deduced that the AM direction also has an influence on the finishing process of the parts. Anwar et al. carried out milling experiments on the titanium alloy block using an end mill in three different feed directions. The three feed directions were: 'feed parallel to the layers' (FPL), 'feed across the layers' (FAL) and 'feed parallel to plane of the layers' (FPPL). The schematic diagram is shown in Figure 2. When the feed direction was FPL, the mean surface roughness was 0.15 μm Ra, which was significantly lower than that of AM as-built parts. Similarly, the values obtained from the situations of FAL and FPPL were 0.12 and 0.13 μm, respectively. Meanwhile, FAL was found to be the best feeding direction to obtain the minimum edge chipping (Anwar et al., 2018). Zimmermann et al. (2020) found that the milling surface roughness with the tool feed direction perpendicular to the build direction was higher in the end milling process of the SLM AlSi10Mg part, when compared with the milling parallel to the build direction. Gong and Li (2019) conducted the milling experiments of SLM 316L stainless steel parts and observed that the forward milling method obtained a better surface roughness, surface quality and edge morphology than the reverse milling method. The grain growth direction of the parts was different due to the different construction direction of AM, and the cutting force was also different in the machining process. The feed cutting force was relatively large in the milling along the growth direction of the columnar grain (Patel et al., 2019).

Matras carried out the semi-finish end milling of the AlSi10Mg alloy parts prepared by the SLM and obtained the surface with low roughness (Ra = 0.14 μm, Rz = 1.1 μm). The surface roughness of the SLM sample could be reduced to more than 20 times by milling. The increase of feed speed and cutting width led to the deterioration of the surface roughness (Matras, 2019). Fortunato et al. conducted the milling process of SLM 18Ni (300) maraging steel, and found that the surface roughness was reduced by increasing the cutting speed. The cutting speed increased from 190 m/min to 380 m/min, and the surface roughness decreased to 0.175 μm Sa (Fortunato et al., 2018). Khorasani et al. used the artificial neural network algorithms to optimise the cutting parameters of five-axis milling of SLM Ti-6Al-4V parts to reduce the surface roughness. It was found that the influence degree of cutting parameters on surface roughness was of the order: feed speed > tool track > spindle speed > annealing temperature > residual height > finishing allowance (Khorasani et al., 2018). Al-Rubaie et al. (2020) found that there was only residual tensile stress on the machined surface of the SLM Ti6Al4V parts and only compressive stress was found on the surface of the stress relief parts in circumferential milling.

**Figure 2** Milling of AM γ-TiAl parts, (a) EBM part (b) schematic diagram of feed direction of milling (see online version for colours)




(a) (b)

*Source:* Anwar et al. (2018)

Grove et al. performed milling tests using the carbide solid end mill for Ti-5553 parts made by conventional forging, SLM and *in-situ* heat treatment during SLM. The hardness of the *in-situ* heat treated parts was 37% higher than that of the forging and SLM, resulting in a 23% increase in the cutting force and faster tool wear (Grove et al., 2018). Park used an uncoated cemented carbide tool to finish the milling of SLM and forged Inconel 718 parts. The results show that the microhardness of the machined surface of SLM parts was lower and the tool life was higher than that of forged parts. Abrasive wear exhibited a great influence on the tool life of AM parts, while adhesive wear and fracture wear mainly occurred on the tools used for forged parts (Park, 2019). Zhang et al. used the femtosecond laser to make nano wavy texture on WC substrate, and then coated with TiAlN coating. Compared with the non-textured tool, when the cutting speed was increased, an improvement in the dry cutting performance of the SLM 316L stainless steel was noted, reducing the cutting force by 10–20%, cutting temperature by 10–15%, and the surface quality of the workpiece was improved (Zhang et al., 2019b).

Parts with high requirements for surface quality and finish require a grinding and mechanical polishing. Guo et al. (2020) used the CBN grinding wheel to improve the surface profile accuracy of EBM Ti-6Al-4V part from 300 μm PV to 7 μm PV, and the surface roughness from 30 μm Ra to about 2 μm Ra by precision grinding, which greatly improved the surface roughness and forming accuracy. Liu et al. compared the grinding performance of the casting and SLM Inconel 718 from grinding wheel wear, surface integrity and other aspects. They found that some internal defects of SLM Inconel 718, such as micro holes and unmelted powder, directly reduced the mechanical strength of the parts, thus reducing the grinding wheel wear rate. However, the surface roughness under microscopic conditions was higher than that of casting parts (Liu et al., 2019). Iquebal et al. reduced the average surface roughness of EBM Ti6Al4V parts from 25 μm Sa to 45 nm Sa, by combining the traditional milling with fine abrasive polishing. As a result, the average roughness of the processed surface decreased by 98.1% and surface hardness increased by 37%. It was also found that the grinding treatment reduced the surface porosity by almost 99.81%, thus providing an effective means to improve the bearing capacity of the AM components (Iquebal et al., 2016).

Raaj et al. grinded the Inconel 718 block plane manufactured by EBM, and performed the low plasticity burning (LPB) from10 MPa to 40 MPa using a sin burning ball of 6 mm. The initial surface roughness of as-built EBM parts was 21 μm Ra, and the surface roughness was improved to about 0.18 μm Ra by grinding. The surface microhardness was increased by about 8% and the tensile residual stress was 300 MPa due to the compressive strain and temperature gradient produced in the surface structure layer during grinding. The porosity was reduced by about 34% compared with the as-built material. After the LPB treatment, the surface roughness was improved to about 0.9 μm, the compressive residual stress was produced on the surface of the workpiece, and the porosity was reduced by 40%. However, due to the effect of pressure, there were some microcracks on the surface. The quality of grinding surface layer was better than that of LPB (Raaj et al., 2020).

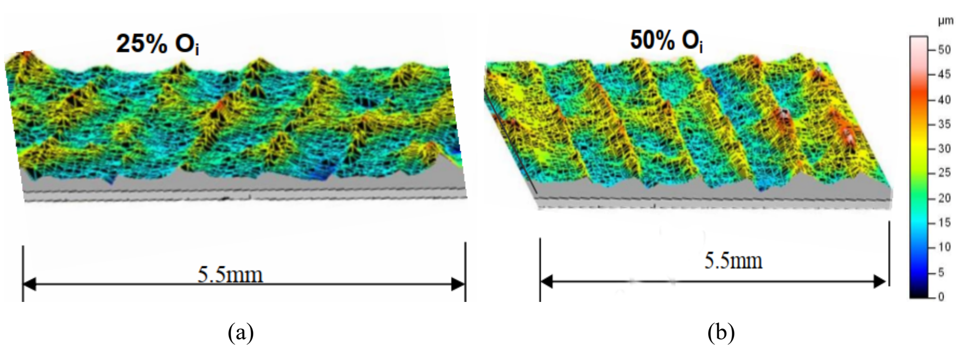
From the results of the mechanical processing of AM parts with regular geometric shape in the above literatures, the mechanical processing can make the parts achieve a very low surface roughness, which can meet the processing requirements of the dimensional accuracy and surface quality of the AM parts. In view of the complex surface, especially the outer surface of the AM parts, the CNC machining technology can also meet the requirements, since it has mature equipment and processing technology in this aspect. However, the mechanical processing method is not suitable for the complex with a closed inner cavity surface and hollow porous structure. Furthermore, the machining method is complex with many processing procedures and has a high cost. Also, the problems like low utilisation of materials and limited adaptability to customised processing requirements of different parts design are encountered. Therefore, mechanical processing can be used for AM parts or partial surface of parts with high machining accuracy and surface quality requirements, such as the blade of aero-engine, blade disc, joint surface of medical implant, and so on. Nevertheless, the machining parameters for AM manufacturing parts need to be further optimised.

## *2.2 Laser polishing*

Laser polishing (LP) is an emerging technology that has the potential to be used to process rough surfaces of AM parts. LP uses laser remelting to thin the surface layer and smoothes the surface by utilising the surface tension effect in the molten pool (Tian et al., 2018). LP process includes laser remelting and laser erosion, both of which use laser beam as heating source to heat the microscopic layer of surface material of parts. Laser remelting is to use continuous laser to scan the solidified layer for the second time, so that the surface can be controlled to melt and re solidified under the condition of protective gas; selective laser erosion (SLE) is to use the energy of pulsed laser beam to evaporate the material to ablate the surface of parts, both of which can reduce the surface roughness and improve the surface quality. LP involves thermodynamics, heat flow physics and surface geometry. In LP of metal objects, two important factors in the interaction region between laser and material need special consideration. The first is the evaporation of the surface material, and the other is the redistribution of surface roughness due to the flow of molten material and surface tension. LP has the advantages of 3D surface automatic machining, consistent surface quality, non-abrasive force interaction, no pollution effect, small area selective polishing and so on. The efficiency of LP is very high. Some experiments show that the surface roughness of parts can be reduced to less than 0.5 μm Ra, and the processing time is very short (Vadali et al., 2012). LP process has been applied to the polishing of diamond coating, optical lens, silicon wafer and other non-metallic materials for more than ten years. There are a few studies on the application of LP in metal surface, some studies have achieved good results in nickel and titanium alloy SLS parts (Lamikiz et al., 2007). At the same time, LP of SLM parts can also be carried out on the SLM manufacturing equipment, by changing and optimising laser parameters for surface polishing, no special equipment is required.

Wang et al. carried out LP of the SLM CoCr alloy parts, and concluded that the most influential factors in the process parameters on surface finish were laser power and material distance. LP effectively controlled the hexagonal dense arrangement and oxide formation of parts, so as to improve the surface structure and corrosion resistance of parts (Wang et al., 2018). Furthermore, Yung et al. (2018) used the optimised LP parameters to improve the surface roughness of SLM CoCr alloy samples with complex surface geometry by 93% and an increase in the surface hardness by 8%.

**Figure 3** Surface topography of different overlap index, (a) overlap index: 25% (b) overlap index: 50% (see online version for colours)

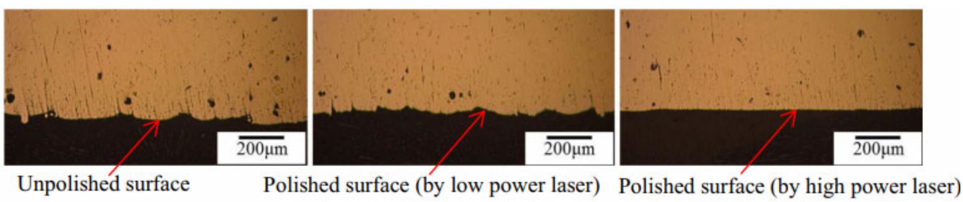



*Source:* Ukar et al. (2010)

Ukar et al. performed LP of AISI 420 stainless manufactured by SLS steel after copper-impregnated treatment. Argon was used as a protective gas to prevent metal oxidation on the parts surface during polishing. Parameters such as laser power, laser beam feed speed and focal length distance (relative position of laser focus and part surface) were optimised to obtain high polishing efficiency and low surface roughness. The initial surface roughness of the parts was 7.5 to 7.8 μm Ra. The average roughness improvement rate after polishing was higher than 80%. However, the roughness after polishing was still higher than 1 μm. They proposed the overlapping index $O_i$ of adjacent laser scanning tracks, and the tests with an $O_i$ of 25%–50% found that the roughness was the lowest when the $O_i$ was 25%, and the surface morphology was shown in Figure 3 (Ukar et al., 2010).

Yung et al. used high-power (more than 100 W) and low-power (less than 100 W) laser for rough and precision polishing of SLM tool steel surface. The average surface roughness Ra of the sample measured by white light interferometer was improved from 12 μm to 0.7 μm Ra. Figure 4 is a comparison of unpolished surface and polished surface (by low power laser and high power laser) of AM tool steel samples. After low-power LP, the surface roughness was improved slightly, but not significantly. However, the surface roughness was significantly improved by high-power LP. The laser energy was applied to the surface, causing heat concentrate and melting of bulge, and the solution flowed into and filled the metal surface with pits (Yung et al., 2019).

**Figure 4** Section topography SLM parts polished by laser (see online version for colours)

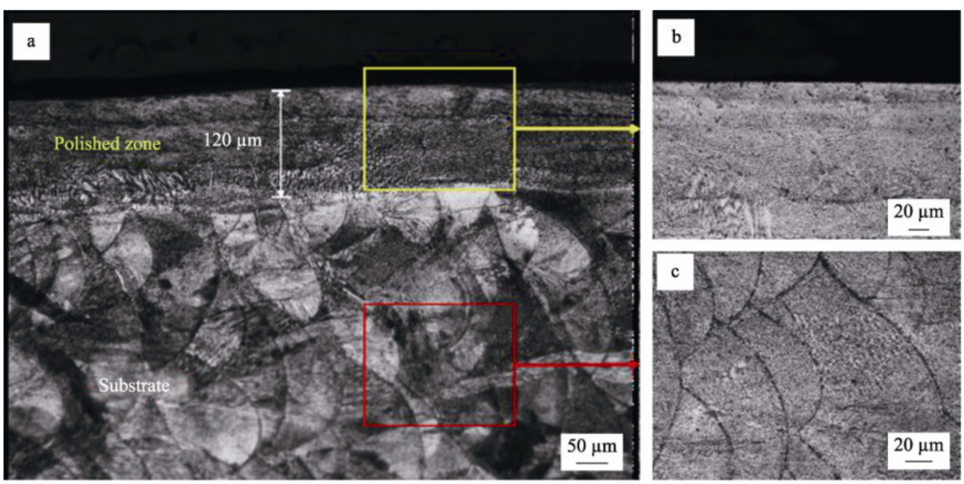



*Source:* Yung et al. (2019)

By employing the process of laser remelting, Yasa et al. reduced the surface roughness of SLM 316L parts from 12 μm to 1.5 μm Ra, increased the density to almost 100%, and improved the surface quality by about 90%, at the cost of a long production time. The microhardness was improved due to the refinement of the microstructure in the laser remelting area (Yasa et al., 2011a). Obeidi et al. (2019) conducted LP of 316L stainless steel cylindrical sample using the continuous wave mode $CO_2$ laser to reduce the roughness from 10.4 μm to 2.7 μm Ra. Chen et al. reduced the surface roughness of AM 316L stainless steel by more than 92% (from 4.75 μm to 0.49 μm Sa) by changing the laser scanning speed and scanning time. No obvious phase transition was observed in the polished subsurface layer, but the microhardness increased from 1.82 GPa to 2.89 GPa (Chen et al., 2020). On this basis, Chen et al. (2021) studied the mechanical properties of the remelted surface layer and found that the tensile strength and plasticity of 316L were improved due to thermal cycling stress, grain refinement, surface defect elimination and dislocation enhancement after LP. Rosa et al. carried out LP of 316L thin-wall parts made by SLS, and adopted multipass strategy to eliminate the microcracks generated during single LP scanning. The best determined parameters included, a laser energy density $E = 525$ J/cm$^2$ obtained with $P = 210$ W, $V_f = 3{,}000$ mm/min, and the overlap rate of scan line was 60%. A final surface roughness of 0.79 μm was obtained after the fifth scan. The laser parameter setting was found to be associated with the initial morphology, material, and part topology. The flow rate of argon gas during polishing also affected the polished surface integrity (Rosa et al., 2015). Rosa et al. (2020) established a regression model for the relationship between the LP parameters and the surface roughness of AM thin-wall parts, based on the experimental data and optimised the process parameters.

Witkin et al. performed the abrasive polishing and laser remelting on a SLM Inconel 625 parts surface to improve the high cycle fatigue performance, but the fatigue performance of the parts after the abrasive polishing was not improved, because the polishing process failed to change the stress concentration of crack or notch surface characteristics. Abrasive polishing made these features shallower, resulting in a significant reduction in the surface roughness without changing their internal structure. Laser remelting appeared to eliminate these types of surface features, improving surface texture and defects, and thus increasing fatigue life (Witkin et al., 2018). Fang et al. polished the SLM Inconel-718 plate samples using laser. The surface roughness of the workpiece decreased from 7.5 μm Ra to less than 0.1 μm Ra, and the microhardness increased from 345 HV to about 440 HV. The thickness of the polished layer was about 120 μm. During the rapid melting and solidification process of the polished layer, along with grain refinement, $\gamma''$ phase deposition caused the microstructure to change with different microstructure from that of the matrix, as shown in Figure 5 (Fang et al., 2018). Liang et al. carried out LP of SLM Ti6Al4V parts, and the thickness of the polishing layer was about 100 μm. Due to the reduced porosity and a complete compact microstructure, LP led to an increase in the surface hardness. It showed a significant reduction in the average Ra value and therefore had a better surface quality (Liang et al., 2020).

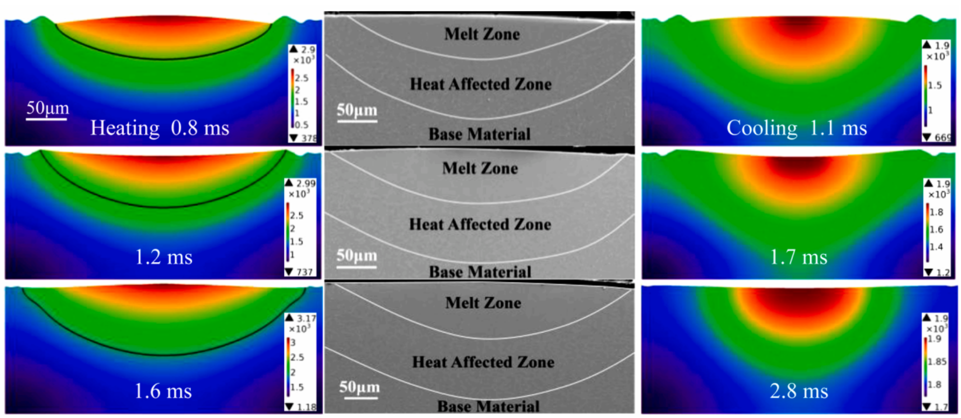
**Figure 5** Cross section of polished Inconel 718 sample from SLM process (see online version for colours)




*Source:* Fang et al. (2018)

Literature show that the LP of AM parts included the optimisation of the laser parameters and control of the molten pool characteristics generated by input energy to obtain the desired re-solidified surface, in order to improve the surface roughness, microstructure and mechanical properties. Tian et al. used LP to improve the surface roughness of the EBM component by more than 75% (measured in mm scale). The surface roughness in microscopic scale was improved to 0.51 μm, which was comparable to the surface of CNC processing, and eliminated the stress concentration defect left by AM process. It was found that the depth of the heat-affected zone extended to the material was 450 μm. The process produced a high level of residual tensile stress (up to 580 MPa) in the surface layer (Tian et al., 2018). Richter et al. studied the remelting performance of SLM Co-Cr-Mo alloy using continuous wave laser, and proposed a method to estimate the molten pool duration based on the geometric relationship between the experimental molten pool and the simulated molten pool. The energy density was determined as a reasonable parameter to estimate the melt duration and critical frequency, and the surface polishing morphology was predicted. The method could be applied to other metal alloys (Richter et al., 2019). Marimuthu et al. used the numerical model based on the computational fluid dynamics to describe the dynamics of SLM TI-6al-4V laser remelting pool. It was found that the input heat energy was the key parameter affecting the convection in the pool. Excessive heat energy input led to the increase of convection velocity, surface oxidation and carbonisation, and produced periodic stripes on the laser polished surface. Low energy input led to higher surface roughness, which should be avoided. By limiting the convection in the molten pool to a minimum, and increasing the width of the molten pool, a good surface profile and roughness was obtained. After optimising the process parameters, the surface roughness after LP was improved from 10.2 μm to 2.4 μm (Marimuthu et al., 2015). Li et al. established a two-dimensional axisymmetric transient numerical model to simulate the surface formation process after laser heating to form a molten pool and cooling of Ti6Al4V. The evolution mechanism of physical processes was revealed to be by heat transfer, thermal radiation, convection, melting and solidification in polishing process. Combined with the experiments, it is found that Marangoni convection played a key role in smoothing the surface of the molten pool. The comparison of the evolution of the molten pool between the numerical simulation and the experiment is shown in Figure 6 (Li et al., 2020).

**Figure 6** Comparison of molten pool evolution between numerical simulation and experimental process (see online version for colours)




*Source:* Li et al. (2020)

Choudhary et al. used the infrared pyrometer to monitor the molten pool of AM NiCrSiBC-60WC ceramic-metal composite during LP. The effects of heat input rate on heating rate, cooling rate, molten pool life and peak temperature were studied and correlated with the surface quality parameters. The combination of medium laser power and scanning speed (600 W and 2,000 mm/min) made the molten pool expand properly and obtain a better surface finish. The surface roughness (Ra) improved from 19.2 μm to

1.75 μm. In addition, a better surface finish was obtained, when the LP was 45° relative to material deposition direction. Surface cracks were observed in all cases, regardless of the process parameters and cooling rate, and matrix preheating alleviated these cracks (Choudhary et al., 2020). Through multiple remelting of SLM Ti6Al4V parts, Karimi et al. (2020) found that with an increase in the number of fusion time, the size and number of hole defects in the parts surface decreased, which resulted in a decrease the porosity, increase in the surface hardness of the sample increased, and homogenisation of the material.

The roughness improvement degree by SLE is less than that of laser remelting, but the efficiency is higher. The combination of SLM and SLE can improve the microstructural processing performance of SLM parts, and can produce internal and external characteristics in the range of 50–100 μm (Yasa et al., 2011b). The results of the study on the influence of the coincidence degree of laser scanning trajectory on surface quality are consistent with those obtained by Ukar et al.

The surface roughness of AM parts is obviously improved by LP, which reduces manufacturing defects caused by the step effect, spheroidising effect and powder adhesion, and changes the microstructure and mechanical properties of surface materials. In the manufacturing process of SLM parts, the secondary remelting of solidified layer by changing laser parameters can significantly reduce the internal defects such as pores and cracks caused by spheroidisation effect, scanning parameters and thermal stress, and make the workpiece more compact, thus improving the mechanical properties of the workpiece. However, there is an unavoidable problem in the application of LP and mechanical processing in AM parts finishing, which is that a large amount of heat will accumulate in the processing area during the processing process of these two processing methods, and it is necessary to control the influence of temperature gradient on the surface quality of the workpiece (Milton et al., 2019; Salonitis et al., 2016). LP is also unable to polish the internal surface of the as-built AM parts.

LP can significantly improve the surface condition of the parts, but the roughness of the laser polished surface is difficult to achieve the effect of mechanical processing. It is suitable for the surface of AM parts with low requirements for surface accuracy and surface roughness, especially for the surface polishing of SLM parts and the treatment of internal defects of the materials. Compared with the traditional mechanical polishing, CP and electropolishing, the advantage of this technology avoids the problems of tool wear, abrasive debris and environmental damage. LP is still in the research and development, and needs an optimisation in its technology.

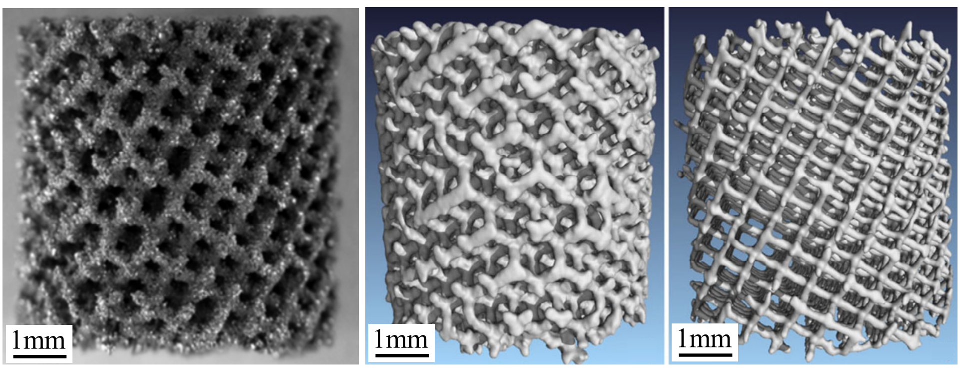
## *2.3 Chemical and ECP*

AM parts with micro porous structure, overall hollow structure or grid structure, such as medical implant metal objects, generally do not require high accuracy of the hole or grid surface, but need to remove the step surface, loose powder particles and solidified spheroidised particles left after the construction process to ensure the required surface smoothness, so as to obtain the surface shape with the required performance. Machining and LP are not suitable for this kind of surface finishing, while chemical and ECP are suitable choices.

CP is a method of eliminating grinding marks and levelling by selective dissolution of the surface roughness on the sample by chemical etching. CP equipment is simple, high production efficiency, can deal with mesh, thin tube and complex shape parts.

Łyczkowska et al. analysed the CP process of Ti-6Al-7Nb alloy scaffold for bone injury prepared by SLM. The scaffold was a porous columnar hollow structure with a diameter of 6.2 mm and a height of 6mm, and the porosity size was from 400 to 420 μm. The material properties and special structure of the parts made it difficult to use the traditional machining process for surface treatment [as shown in Figure 7(a)]. Two kinds of solutions: 80% $H_2O$, 6% HF (hydrofluoric acid) and 14% $HNO_3$ (nitric acid), 99% $H_2O$ and 1% HF were used for CP in ultrasonic cleaning machine and magnetic stirrer for 60, 80, 90, 600, 700 and 900 s respectively. The effectiveness of the CP process has been confirmed by using a microcomputer to perform tomography (mCT) and three-dimensional model reconstruction of the polished samples, as shown in Figures 7(b) and 7(c) (Łyczkowska et al., 2014).

**Figure 7** Ti-6Al-7Nb alloy scaffold for bone injury, (a) SLM scaffold (b) tomography (mCT) model before polishing (c) tomography (mCT) model after polishing (see online version for colours)




(a) (b) (c)

*Source:* Łyczkowska et al. (2014)

The polishing process in the ultrasonic cleaning machine is unstable and difficult to control, which easily leads to the phenomenon of excessive polishing of the scaffold surface. In the solution composed of distilled water and hydrofluoric acid, the polished sample surface is more regular. Reducing the concentration of acid solution and prolonging the immersion time can avoid the cavity caused by high concentration of acid solution, and still successfully remove the unmelted powder particles adhered on the surface; at the same time, the polishing process can be better controlled. Magnetic stirrer polishing ensures greater process stability. CP process can batch process SLM parts.

Wysocki et al. used industrial pure titanium powder and SLM method to prepare the scaffolds with double pore diameters (200 μm in the central part and 500 μm in the peripheral part). The parts were chemically polished in HF/$HNO_3$ solution to remove the unmelted powder particles, and the Young's modulus of the grid structure of the SLM parts was reduced from 42.7 GPa to 13.3 GPa, which was very similar to the Young's modulus of the human living bone. It was pointed out that the polishing process needs to be optimised for the parts with different mesh sizes (Wysocki et al., 2019).

Balyakin et al. studied the surface roughness of the SLM Ti6Al4V samples after heat treatment, surface brushing and CP (an aqueous solution containing 10% HF and 10% $HNO_3$ was used as an etching agent at 25°C and 50 mL in volume). It was found that the surface roughness was the lowest, Ra = 0.27 μm, Rz = 2.38 μm, after annealing at 650°C for 2 h, water quenching at 950°C, and brushing and CP (Balyakin et al., 2019b). Balyakin et al. also studied the CP effects after brushing and abrasive machining on the sample surface. The initial and processed surface roughness of the SLM Ti6Al4V specimens are shown in Table 1. Moreover, the residual compressive stress (about 1 MPa circumferential tensile residual stress at the initial stage) on the surface of the specimen was generated by machining. The peak value of brushing at 105 μm depth was 17 MPa, which was not obvious. The peak value of abrasive sandblasting at 109 μm depth was 283 MPa (Balyakin et al., 2019a). Scherillo et al. treated the EBM Ti6Al4V parts in HF and $HNO_3$ acid solutions with different $HF/HNO_3$ solution molar ratios. The smoothing process was divided into two steps. In the first step, the unfused particles on the surface were removed, and in the second step, the characteristic peaks were selectively dissolved. In this process, the transport properties of the solution played a key role, and the increase of nitric acid concentration led to the increase of solution viscosity, low transport performance and enhanced smoothing ability (Scherillo et al., 2020).

**Table 1** Surface roughness of SLM Ti6Al4V specimens

| *Surface treatment* | *Machined specimens* | | | *Chemically treated specimens* | | |
|---|---|---|---|---|---|---|
| | *No matching* | *Brushing* | *Abrasive machining* | *No matching* | *Brushing* | *Abrasive machining* |
| Longitudinal roughness Ra, μm | 4.88 | 1.70 | 2.13 | 0.38 | 0.38 | 0.31 |
| Transverse roughness Ra, μm | 5.40 | 1.90 | 2.42 | 0.43 | 0.41 | 0.37 |

*Source:* Balyakin et al. (2019a)

ECP is to modify the chemical solution by adding oxidant, and form a passive film on the surface of the workpiece by electropolishing process (ECP) to improve the surface quality. Habibzadeh et al. developed a new solution for electropolishing of 316L stainless steel medical implants. It was found that the passive oxide film formed on the electropolished surface enriched chromium during the ECP. Compared with the passive film naturally growing on the untreated (controlled) surface and bulk phase, the EP surface had a positive effect on the attachment of endothelial cells and smooth muscle cells, showing a lower degree of thrombosis. ECP technology can be used to treat the surface of 316L-SS, which can significantly improve the performance of implant materials (Habibzadeh et al., 2014). Alrbaey et al. carried out the ECP of the remelting surface for SLM 316L stainless steel using a choline chloride ionic electrolyte. By optimising the process parameters, the average surface roughness was improved by 75%, the optimised Ra was less than 0.5 μm, and the fatigue life of the parts was increased by about 20% by polishing the surfaces under 4 V potential for 30 minutes at 40°C (Alrbaey et al., 2016). Cruz et al. used 0.58% w/V NaCl electrolyte for ECP at ambient temperature to study the corrosion characteristics of SLM-316L under different residual compressive stress. It was found that with the decrease of residual compressive stress, the dynamic characteristics of passive film growth and re passivation was reduced, and the resistance of pit initiation was increased (Cruz et al., 2020). Kim and Park carried out the high current density (3.2, 6.5 and 8.6 $A/cm^2$) ECP of AM 316L stainless steel in a 60°C electrolyte mixed with sulphuric acid (2.4 M $H_2SO_4$), phosphoric acid (5.9 M $H_3PO_4$) and ultra-pure water. The metal dissolution was more active than that under conventional current density, which maximised the surface mass and improved the surface corrosion resistance (Kim and Park, 2019). Bai et al. used the advanced dry mechanical electrochemical polishing (DMECP) technology to process the SLM 316L stainless steel parts. DMECP combines the advantages of the mechanical polishing and ECP, thereby making it more environmentally friendly. The roughness of the top surface of the workpiece was improved from 8.72 μm to 0.75 μm Ra, which was more than 91% lower than that of the as-build part. The reduction rate of the side surface was more than 93% (from 12.10 μm to 0.80 μm Ra). The secondary defects formed in the polishing process were removed by the mechanical polishing. The results show that DMECP was an effective technology to improve the surface quality and mirror finish of the SLM parts (Bai et al., 2020).

Zhang et al. carried out ECP of SLM Inconel 718 pipe. After ECP treatment for one min, the particles attached to SLM Inconel 718 sample surface were completely peeled off. After ECP treatment for 4–5 minutes, smooth and flat surface was obtained, and the surface roughness decreased from 6.05 μm to 3.66 μm Ra. The nano-indentation results showed that the ECP treated samples had lower microhardness and elastic modulus due to the dissolution of hardening phase and release of residual stress (Zhang et al., 2017). Urlea and Brailovski performed the ECP of SLM Ti-6Al-4V parts oriented from 0 to 135° relative to the building platform at the volume ratio of perchloric acid (60%) and glacial acetic acid of 1:9. The initial surface roughness range was from 4 μm (0°) to 23 μm (135°) Ra and polished to uniform roughness 1–3 μm Ra. The surfaces constructed in the direction of 22.5° to 112.5° had a very similar initial surface finish, with a 92%improvement in surface finish (Ra) (Urlea and Brailovski, 2017). The unique surface of the EBM industrial pure titanium part was post treated under the conditions of 10–30 V and 10–600 s by Jung et al. The surface was completely flattened and the original surface characteristics disappeared after 600 s of electropolishing at 20 V and 30 V. With the increase of voltage and time, the surface roughness value decreased (Jung et al., 2017). The surface of EBM Ti-6Al-4V parts precisely ground by CBN grinding wheel was electropolished by Guo et al. The surface roughness of 2 μm Ra was improved to a value less than 0.65 μm Ra, and the surface work hardening caused by grinding was improved (Guo et al., 2020).

ECP shows a remarkable polishing effect on metal parts with initial roughness of about 1 μm Ra, which can reach the mirror level. But the surface roughness of the additive manufacturing (AM) component is much higher than 1 μm Ra. Moreover, the ECP method cannot guarantee the selective material removal in different areas of the complex shape parts, resulting in the size of the polished parts seriously out of tolerance (Huang et al., 2008).

The polishing precision and roughness of the chemical and ECP exhibit an inferior quality than those of the mechanical processing (the comparison is shown in Table 2). However, it quickly and efficiently eliminates the surface defects of porous, exhibits a mesh or special-shaped hollow structure, makes the processed surface smooth and meets the service performance requirements. In the field of medical implantation, AM titanium alloy mesh scaffolds are used to fill bone loss caused by injury or disease and AM joint implants are used to replace the injured joints that need to adapt the micropores, mesh and hollow structures to facilitate the bone tissue growth on the implant surface. Some AM components used in the aerospace equipment are also designed as grids or hollow supports to reduce the weight. Chemical and ECP techniques can be applied to the polishing of the complex structures of such parts. In addition, it is suggested to use green corrosion solution.

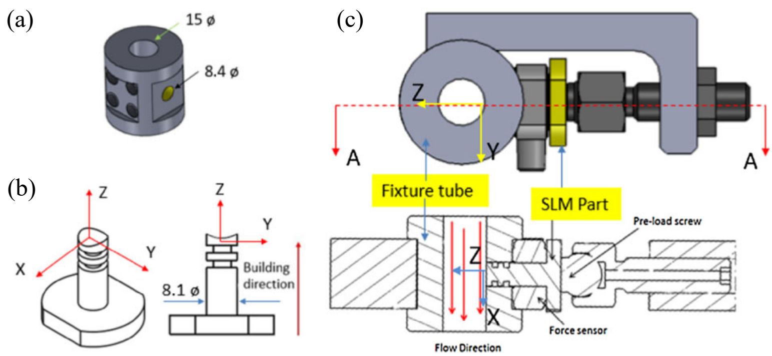
### *2.4 Abrasive flow machining*

AFM can be used for external surface polishing of the conventional and AM parts, and also in the polishing of internal holes. Metal AM has been used to form moulds with shaped water cooling channels, cutters with coolant passages, jet engine nozzles and special-shaped oil channels. The internal flow passage of the AM parts needs to bear a high pressure and high speed flow impact of liquid. Only low surface roughness and high surface quality of the flow passage can guarantee the performance and fatigue life of the parts. Therefore, it is necessary to finish the internal flow passage. Mechanical processing and LP methods are not suitable, and the chemical and ECP techniques are difficult to achieve the desired results.

Kumar and Hiremath (2016) analysed the AFM influencing factors, considering mainly from three aspects: AFM processing equipment performance, abrasive media and workpiece materials. Gorana et al. carried out the AFM of parts with different abrasive particle sizes (mesh 80 and 220) and abrasive concentrations (40% and 60%). It was found that when the grain size and concentration of the medium were large, the rate of decrease of the surface roughness Ra was low, indicating that the grain size and abrasive concentration influenced the evolution of the surface roughness (Gorana et al., 2006). Kenda et al. carried out AFM treatment on the electrical discharge machining (EDM) surface of tool steel AISI D2 and measured the residual stress on the surface layer. The tensile residual stress was produced on the surface of EDM, while the compressive residual stress was produced under the surface after AFM. The residual compressive stress increased, with an increase in the extrusion pressure of AFM (Kenda et al., 2011). Jain and Adsul (2000) found that the lowest surface roughness reached 0.4 μm Ra in the AFM test of brass and aluminium. Khorasani et al. conducted the wet abrasive centrifugal barrel finishing (WACBF) of SLM 316L stainless steel blocks, and found that by increasing the size and mass of grinding medium, including enhancing the flow of the abrasive, a greater pressure was exerted in the polishing process, thus removing more material and improving the surface quality. When the speed of abrasive drum was 140 rpm, the medium size was 6 mm and the processing time was 200 min, the surface quality of the workpiece was found to be the best, and the roughness of each surface of the parts increased by more than 56% (Khorasani et al., 2020). Hassanin et al. (2020) applied a rotational speed to the SLM AlSi10Mg alloy sample during the AFM polishing to improve the polishing efficiency and the smoothness of the workpiece surface.

In most AFM processes, a special fixture was designed to include the polished open surface in the abrasive flow channel, or the two ends of the hole of the workpiece were connected to form the abrasive flow channel. The viscoelastic abrasive medium was driven to flow back and forth on the polished surface of the workpiece by the pressure action; so as to remove the micro amount of surface materials, realise the deburring, guiding circle, polishing and other processing (Uhlmann et al., 2016). AFM of heat-treated maraging steel 300 SLM parts was performed using a different polishing medium with different abrasive concentration and medium viscosity by Duval-Chaneac et al. It was found that with an increase in the concentration and the viscosity of the abrasive, a decline was observed in the surface roughness. Residual compressive stress occurred on the machined surface (Duval-Chaneac et al., 2018). The ploughing mechanism of the as-built SLM parts in the AFM process was more than that of heat-treated maraging steel part, so the residual compressive stress was greater than the latter. Due to the open surface of the polished part, a special fixture was designed to overlap the surface of the part with the surface of the flow channel in the fixture tube, and the part through the positioning was fixed and clamping mechanism, and drive the abrasive flow in the fixture tube by the air cylinder for surface polishing, as shown in Figure 8.

**Figure 8** Schematic diagram of fixture for AFM, (a) SLM part (b) fixture tube (c) fixture (see online version for colours)




*Source:* Duval-Chaneac et al. (2018)

Conformal cooling channels are widely used in the mould industry, as they can achieve a rapid and uniform cooling effect in the injection moulding process. Moulds with complex conformal cooling channels can be manufactured by powder-bed AM. However, the surface roughness of the inner channel was high, about 10 μm Ra, which affected the fatigue life of the mould. AFM has a high machining accessibility, and presents obvious advantages in polishing complex internal cavity structure and complex internal flow passage (Shao and Cheng, 2019). The finishing process of the untouchable internal hole surface internal complex shape parts manufactured by AM is possible. For the AFM polishing fixture of pipes, it is necessary to design a channel plate and funnel at the two ports of the pipe, connect the funnel with the driving cylinder block, and form a closed abrasive channel under the action of positioning and clamping mechanism, as shown in Figure 9.

Mohammadian et al. tried to combine the CP and abrasive flow polishing to polish the inner surface of IN625 tubular parts designed for the aerospace industry. They designed three kinds of polishing solutions:

a abrasive particle flow suspended in water

b chemical solution flow without abrasive

c abrasive particle flow suspended in chemical solution.

**Table 2** Comparison of finished surface roughness and performance of different finishing techniques

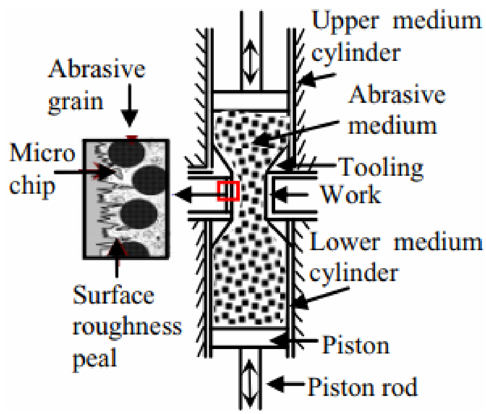
| *Sl. no.* | *Authors* | *Part* | *Post-treatment technology* | *Finished surface roughness* | *Remarks* |
|---|---|---|---|---|---|
| 1 | Rotella et al. (2018) | EBM Ti6Al4V<br>DMLS Ti6Al4V<br>Forging Ti6Al4V | Semi-finish turning | 1.90~1.30 μm Ra | *Mechanical processing*<br>Strengths:<br>• high machining accuracy and surface roughness<br>• Mature equipment and processing technology<br>Weaknesses:<br>• Multiple processing procedures and high cost<br>• Machining of complex approximately closed cavity surfaces, pores, and hollow-out porous structures<br>• Optimisation of machining parameters of AM parts |
| 2 | Coz et al. (2020) | SLM Ti6Al4V | Finish turning | 0.004~0.36 μm Rt | |
| 3 | Anwar et al. (2018) | EBM $\gamma$-TiAl | Finish milling | 0.12~0.15 μm Ra | |
| 4 | Matras (2019) | SLM AlSi10Mg | Semi-finish milling | 0.14 μm Ra, 1.10 μm Rz | |
| 5 | Fortunato et al. (2018) | SLM 18Ni (300) | Finish milling | 0.175 μm Sa | |
| 6 | Iquebal et al. (2016) | EBM Ti6Al4V | Finish milling and abrasive polishing | 0.045 μm Sa | |
| 7 | Raaj et al. (2020) | EBM Inconel 718 | Precision grinding | 0.18 μm Ra | |
| 8 | Yung et al. (2018) | SLM CoCr | Laser polishing | 0.70 μm Sa | *Laser polishing*<br>Strengths:<br>• Elimination of pores and defects of the surface<br>• Improvement of surface quality, density and mechanical properties<br>Weaknesses:<br>• Polishing of complex internal structures<br>• Thermal damage of the surface layer<br>• Less application data |
| 9 | Yung et al. (2019) | SLM tool steel | Laser polishing | 0.73 μm Ra | |
| 10 | Chen et al. (2020) | SLM 316L | Laser polishing | 0.49 μm Sa | |
| 11 | Rosa et al. (2015) | SLS 316L | Laser polishing | 0.79 μm Ra (fifth scan) | |
| 12 | Fang et al. (2018) | SLM Inconel 718 | Laser polishing | 0.10 μm Ra | |
| 13 | Tian et al. (2018) | EBM Ti6Al4V | Laser polishing | 0.51 μm Sa | |
| 14 | Choudhary et al. (2020) | NiCrSiBC-60WC | Laser polishing | 1.75 μm Ra | |

**Table 2** Comparison of finished surface roughness and performance of different finishing techniques (continued)

| *Sl. no.* | *Authors* | *Part* | *Post-treatment technology* | *Finished surface roughness* | *Remarks* |
|---|---|---|---|---|---|
| 15 | Balyakin et al. (2019b) | SLM Ti6Al4V | Brushing + chemical polishing | 0.27 μm Ra<br>2.38 μm Rz | *Chemical and electrochemical polishing*<br>Strengths: |
| 16 | Alrbaey et al. (2016) | SLM 316L | Electrochemical polishing | Less than 0.5 μm Ra | • Improvement of surface roughness |
| 17 | Bai et al. (2020) | SLM 316L | Dry mechanical electrochemical polishing | Top surface: 0.75 μm Ra<br>Lateral surface: 0.80 μm Ra | • High efficiency of batch processing<br>• Elimination of surface defects of porous, meshwork or special-shaped hollow structures |
| 18 | Zhang et al. (2017) | SLM Inconel 718 | Electrochemical polishing | 3.66 μm Ra | Weaknesses: |
| 19 | Urlea and Brailovski (2017) | SLM Ti6Al4V | Electrochemical polishing | 1~3 μm Ra | • Non-environmental solution |
| 20 | Guo et al. (2020) | EBM Ti-6Al-4V | Precision grinding + electrochemical polishing | 0.65 μm Ra (curved surface) | • Requirements for initial surface roughness and electrode shape in electrochemical polishing |
| 21 | Jain and Adsul (2000) | Brass and aluminium | Abrasive flow polishing | 0.40 μm Ra | *Abrasive flow polishing* |
| 22 | Khorasani et al. (2020) | SLM 316L | Wet abrasive centrifugal barrel finishing | 2.01~3.37 μm Ra | Strengths: |
| 23 | Mohammadian et al. (2017) | Inconel 625 | Chemical polishing + abrasive flow polishing | 14.20 μm Ra | • Improvement of surface roughness and fatigue performance of the part |
| 24 | Han et al. (2020a) | SLM maraging steel 300 | Abrasive flow polishing | 1.30 μm Sa | • Processing of conformal holes<br>Weaknesses: |
| 25 | Karakurt et al. (2018) | EBM copper | Magneto abrasive flow machining | 4 μm Ra | • Requirement of special fixture |
| 26 | Zhang et al. (2019a) | SLM 316L | Magneto abrasive flow machining | Less than 5 μm Ra | • The concave part of the rough surface cannot be completely removed |
| 27 | Teng et al. (2019) | SLM AlSi10Mg | Grinding + magneto abrasive flow machining | 0.155 μm Ra | |

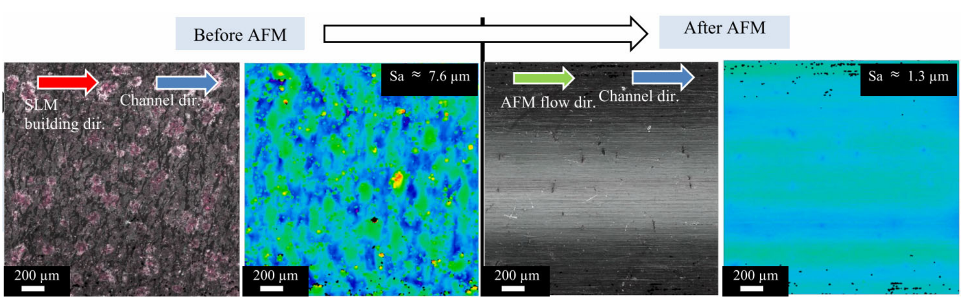
The synergistic effect of the chemical flow and abrasive flow was studied. Compared to the CP or abrasive flow polishing alone, the combination of the CP and abrasive flow polishing improved the surface roughness by two times, and the polishing time was reduced from 3 h to 1 h. Chemical abrasive flow polishing removed the semi welding particles on the surface. For 15° construction direction, the Ra value was reduced by about 45%, and for 135° construction direction, the Ra value was reduced by 20%. The fluid velocity or the length of the polishing time was directly proportional to the polishing depth, irrespective of the kind of polishing technology (Mohammadian et al., 2017).

**Figure 9** Schematic diagram of AFM fixture of pipe (see online version for colours)




*Source:* Kumar and Hiremath (2016)

**Figure 10** Roughness comparison of the straight channel before and after AFM (see online version for colours)




*Source:* Han et al. (2020a)

Han et al. compared the surface morphology and roughness of the internal cylindrical hole of the SLM 300 maraging steel after EDM and AFM. It was found that the initial roughness parameters, such as the micro surface roughness Sa, were significantly reduced due to the effect of abrasive particles on the roughness peak in AFM process. However, due to the difficulty of the abrasive particles in reaching the deep valley, the roughness barranco was not improved significantly. AFM improved the anti-fatigue performance of the channel by 26%, which was similar to that of EDM (Han et al., 2020b). They used the AFM method to polish the single or multi-channel linear and spiral conformed SLM cooling channels. The results showed that the roughness of the SLM conformal cooling channel was effectively improved by the AFM. Through AFM finishing, the arithmetic average height of the straight conformal cooling channel surface was decreased from 7.6 μm Sa to 1.3 μm Sa, as shown in Figure 10. Under the same finishing condition, the polishing effect of the spiral channel was slightly worse than that of straight channel. The number, length and flux of abrasive media affected the polishing effect (Han et al., 2020a). The polished surface was left with the flowing abrasion marks of abrasive media, and the concave part of the original rough surface was not completely removed. During the AFM processing, the abrasive particles caused the plastic flow of the surface material of the workpiece, resulting in the compressive residual stress on the surface (Han et al., 2020c).

Based on the AFM technology, Singh and Shan (2002) developed the magneto flow process (MAFM) to control the abrasive flow characteristics by applying a magnetic field around the workpiece, thus further improving the polishing efficiency and surface roughness. Teng et al. polished the SLM AlSi10Mg alloy by using a combination of the grinding process (GP) and magnetic abrasive finishing (MAF). GP used 160–200 μm $Al_2O_3$ series mixed abrasives. MAF used SiC W7, SiC W40 and $Al_2O_3$ W7 spherical magnetic abrasives prepared by the rapid solidification gas atomisation. The surface roughness of the sample after GP was about 0.6 μm, and there were many scratches and pores. Subsequently, three kinds of magnetic abrasives were used in the MAF test, and good results were obtained. SiC W7 magnetic abrasive was used to process the surface roughness with a minimum of 0.155 μm and exhibited a good surface morphology. The surface roughness during MAF using $Al_2O_3$-W7 magnetic abrasive was improved rapidly, which depended on the number of the abrasive particles adhering to the magnetic abrasive surface. In addition, the surface after GP was machined hard, and MAF made the machined hard layer shallower, thereby reducing hardness (Teng et al., 2019). Karakurt et al. applied the MAFM in the polishing of EBM copper structure. Preliminary polishing results showed that the surface roughness was greatly improved, from about 35 μm to 4 μm of average surface roughness (Ra) (Karakurt et al., 2018). Zhang et al. implemented MAFM of SLM 316L stainless steel, the surface roughness was improved by 75.7% at most. The surface roughness was associated with the grinding grain of indentation depth, the material removal rate analytical model was established, and the amount of total removal of MAF processing of materials was finally obtained (Zhang et al., 2019a).

Through the analysis of the references, the surface roughness of finished AM parts and the performance of different finishing technologies are summarised, as shown in Table 2.

## 3 Conclusions

By analysing the finishing process of the AM metal parts, the evolution rules of the surface roughness, material removal and surface residual stress were clarified. The material removal mechanism, processing effect and adaptability of the different finishing techniques were analysed.

Mechanical processing is the most important processing method to obtain the precision and surface quality of parts in the subtractive manufacturing. The processing equipment and technology are very mature. Very high surface quality was also obtained in the AM parts finishing using mechanical processing. On the premise that the CNC processing ability met the requirements, the machining method met the processing requirements of the dimensional accuracy and surface quality of the AM parts, such as blade of aviation engine, blade disk, joint surface of medical implant bone, etc. The disadvantages were complex application process, many processing procedures, low material utilisation rate and high cost. Machining methods were not an effective form of processing for complex closed inner cavities, channels, or hollow porous structures.

LP is mainly used for polishing and strengthening the surface of AM parts. By adjusting the process parameters and using SLM equipment, mixed processing of additive and laser remelting was conducted, which significantly improved the surface smoothness, reduced surface defects, and improved the surface density and mechanical properties. The process did not require the involvement of tools and polluting solvents. The disadvantages were that LP could hardly avoid the impact of a large amount of heat on the surface of the workpiece as like the mechanical processing. Furthermore, the precision and roughness of the processed surface were worse than that of mechanical processing, and only the surface directly irradiated by laser could be processed.

CP can carry out batch processing on AM parts, and can deal with parts with complex surface of porous and grid structure, so as to obtain a microscopic smooth surface. It is a good choice for the surface treatment of microhole, mesh and hollow structure of medical implants and aerospace parts with low shape accuracy requirement. ECP can further improve the polishing precision, surface quality and efficiency of parts, but it requires high initial surface roughness and electrode shape. CP and ECP can hardly avoid the use of polluting corrosive liquid.

AFM has great advantages in the finishing of the complex flow channels inside parts. With the help of special fixture design, open complex surfaces (such as blade disk) can also be machined. The development of the magnetorheological technology further expands the application space of the abrasive flow.

Thus, the four finishing technologies have their different inheritant advantages and disadvantages. According to the surface characteristics and post-processing requirements of AM parts, the finishing methods can be matched, and then the surface treatment of AM parts can be carried out efficiently and with high quality.

## 4 Areas of future work

The AM of the metal materials has been successfully applied in aerospace, military, medical, automobile and other fields. Metal powder-bed AM technology has become one of the most important and widely used metal AM technologies with its advantages of adaptability, short process cycle and high forming accuracy.

It is difficult to obtain high strength and toughness, high density, uniform structure, high quality surface and high dimensional accuracy at the same time for metal AM components manufactured. Hence, the parts, especially their surfaces, must be reprocessed. The commonly used post-treatment processes of AM components include the heat treatment, surface strengthening treatment and the finishing processing. Heat treatment and surface strengthening treatment improve the material structure, internal defects, mechanical properties and service properties. Finishing process improves the precision and surface quality of the parts, while avoiding the surface stress concentration. The traditional finishing processing technology can be applied to the surface post-treatment of AM parts. The matching of the finishing methods is carried out according to the requirements of finishing for the different parts. At the same time, with the development of AM materials, manufacturing technology and service requirements of the parts, finishing processing technologies are being optimised and innovated. The development trend of the application of finishing technologies of AM parts is as follows:

1 AM technology and process can be optimised to improve the surface accuracy and the quality of AM parts. The manufacturing process of AM parts is optimised from the aspects of powder characteristics, process parameters and scanning strategy, so as to obtain a high-precision and high-quality surface and simplify the finishing processing process.

2 Finishing standard system of AM metal parts can be established. The performance evaluation system and application evaluation criteria for different finishing methods on the surface finishing process of the metal AM components are established to realise the standardisation and optimisation of the application of finishing methods in AM parts.

3 With the innovation and development of the electrical, optical, material, computer software, machinery and other fields of professional technology, additive technology is moving towards material mixing ratio, application of various new materials, etc. and the surface finishing technology of parts will also develop and be innovated accordingly.

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