Influence of electrolyte flow on plasma electrolytic polishing of additively manufactured lattice structures

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Abstract

Additive manufacturing enables the production of complex geometries such as lattice structures, widely used in aerospace and medical applications for their high strength-to-weight ratio. However, achieving a high-quality surface finish on internal features remains a challenge. Plasma electrolytic polishing (PEP) offers a promising solution. The process is like electro chemical machining (ECM), but the electrolytes are low concentration salts dissolved in water and with much higher voltage, hence the vapor-gaseous envelope is formed around the workpiece. The Faraday effect limits the polishing of lattice structures but forced electrolyte flow may improve the polishing of internal structures. This study investigates the effect of flushing through a BCC lattice structure using a custom nozzle during PEP. Cross-sectional analysis of lattice structures shows that 4 l min^{-1} flow achieved the greatest material removal across all layers. Increasing the flow rate resulted in lower material removal rate, most likely due to the disruption of the vapor-gaseous envelope. The results, supported by strut diameter evolution across layers, emphasize the importance of optimizing electrolyte flow to effectively polish internal features.

Keywords: Plasma Electrolytic polishing, additive manufacturing, lattice structures, Electrolyte flow rate

1 Introduction

Additive manufacturing (AM) is becoming increasingly popular due to its versatility in producing structures of higher complexity that can be customised depending on the application. Lattice structures are one of these structures that are easier to produce with AM and are widely used in the automotive, aerospace and energy industries due to their good strength-to-weight ratio.

Laser and Electron Powder Bed Fusion (PBF-LB/EB) are the most used AM techniques for the production of metal parts. The surface quality of parts produced with metal AM is lower than industry requirements. This is mainly due to the geometrical approximation caused by the layer-by-layer manufacturing process, orientation-dependent surface anisotropy caused by partially melted powder particles adhering to the surfaces due to poor heat transfer to the base plate, and balling defects, etc. [1]. These surface defects can increase the risk of corrosion and even reduce the fatigue properties of the parts. To realise the true potential of the AM process, post-processing steps have become an integral part of the workflow. There are many techniques that have been developed over the years to overcome this challenge, and it is one of the most studied areas in the field. Laser polishing, abrasive polishing, mechanical polishing, chemical and electrochemical polishing and electro-discharge assisted finishing are some of the existing techniques used to improve the surface quality of AM metal parts. Chemical, electrochemical and abrasive polishing processes are used for complex structures such as lattices.

Plasma electrolytic polishing (PEP) is a relatively new technique for polishing AM metal parts. PEP is similar to electrochemical techniques but operates at a much higher voltage range and uses less toxic, low concentrated salt-based aqueous electrolyte. PEP improves surface integrity through anodic dissolution and plasma reactions [2]. In this process, an anodically polarised part is immersed in an electrolyte tank, which is used as a cathode or with a cathode electrode in the tank. At favourable voltages (depends on the electrolyte -material combination), a vapour-gas sheath forms around the part to be polished, acting as a virtual cathode around the part and leading to plasma formation, which enables the processing of more complex structures without the challenges of special tools [3].

The feasibility of PEP in polishing structures such as lattices is less researched [4], [5], [6]. The existing studies show that polishing the internal depth of lattices is difficult due to electric field shielding effects and the entrapment of gas bubbles in narrow cavities, affecting polishing performance. Process modifications such as an internal forced electrolyte flow directed towards the samples are possible solutions to improve polishing performance. Preliminary investigations have shown that optimisation of the flow parameters is required to achieve the best results [6]. In this study, the influence of different flow rates on the polishing performance over the depth of simple BCC lattice structures during PEP is investigated. Figure 1 shows the schematic diagram of the PEP setup with internal forced electrolyte flushing system.

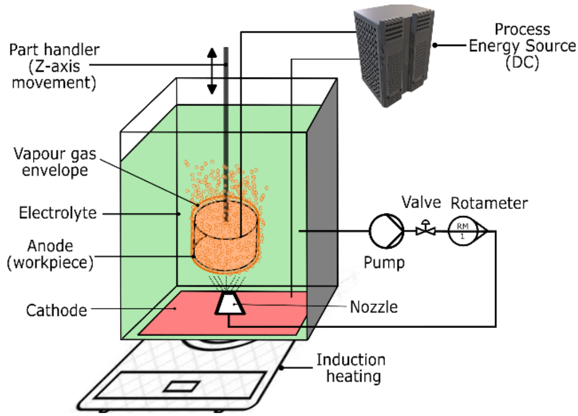

Figure 1: *Schematic diagram of PEP setup with internal forced electrolyte flushing system*

2 Material and methods

Lattice structure made of stainless steel 316L made with PBF-LB were used for the study. The size of the lattice structure is a cubic block of 25 mm^3 (Figure 2) with BCC unit cells with a theoretical strut diameter of 0.5 mm and 5 cells along the length (relative density of 3.27%). These dimensions of the lattice structure were chosen based on the results of a previous study [6].

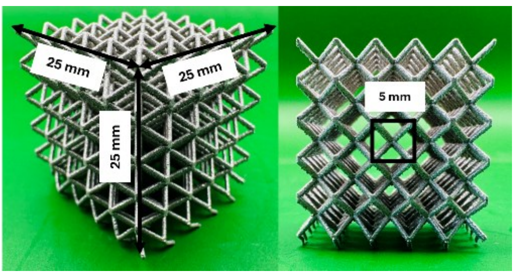

Figure 2: *BCC lattice structure fabricated using PBF-LB/M technique*

The PEP experiments were carried out with an ammonium sulphate-based electrolyte at 75°C and a voltage of 320 V. All samples were polished for 3 minutes. The forced electrolyte flow varied in three stages of 2,4 and 6 l min^{-1} through a custom-made nozzle (exit diameter = 30 mm). The design of the nozzle was customised based on the results of the preliminary studies to allow an electrolyte flow covering the entire lattice structure. The customised nozzle was printed using the Fused Deposition AM technique and aligned in the electrolyte tank to enable efficient removal of the bubbles formed in the internal cavities (Figure 3 (a)). The orientation of the lattice with respect to the nozzle outlet is classified as layer 1-5 as shown in (Figure 3 (b & c)).

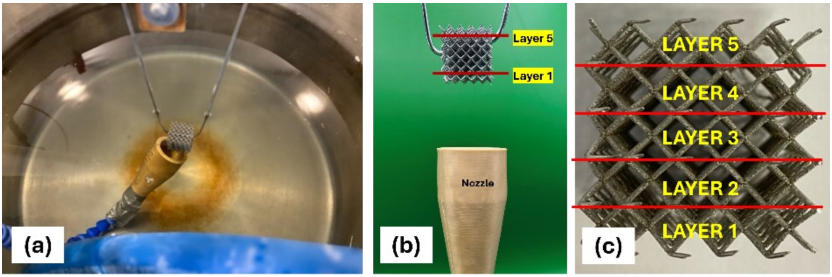

Figure 3: *(a) Installation of the custom nozzle inside the electrolyte tank, (b) lattice arrangement with respect to nozzle outlet and (c) layer classification based on the lattice arrangement in the electrolyte.*

The samples before and after PEP treatment were characterised using a Keyence VHX 7000 series optical microscope.

3 Results and discussions

The effectiveness of PEP polishing of lattices was analysed by examining the surface quality and variations in lattice strut diameters after different polishing conditions. The surface of the as-built lattices is very rough, which is mainly due to partially melted powder particles adhering to the surface (Figure 4). The diameter of the lattice struts (0.795±0.031 mm) has changed compared to the original CAD (0.5 mm). This could be due to the partially melted powder having a greater tendency to adhere due to poor heat transfer.

A series of experiments were performed without flow to compare the effect of polishing with forced internal electrolyte flow. The microscopic images of as-built lattice and the first layer for BCC lattices polished without and with 2, 4 and

6 l min^{-1} are shown in Figure 5. Layer 1 is the critical layer that has the greatest influence of PEP. In case of polishing with forced electrolyte flow, it is the first area where the forced flow impacting (Figure 3). In the case of polishing

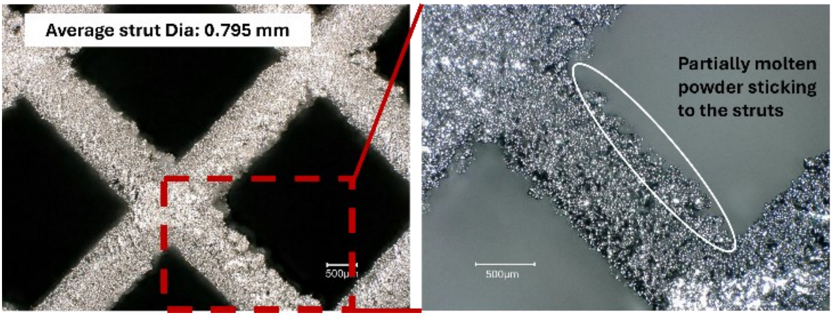

Figure 4: *Surface images of as-built lattice struts*

without flow, it is the lowest layer in the electrolyte tank (this also applies to the setup with flow (Figure 3). Therefore, the effect of polishing is greatest as the thickness of the vapour layer is smallest there and the bubbles rise continuously, introducing fresh electrolyte at the point where polishing works best. In PEP with forced flow, the effect of the flow is greatest in the layer 1, and the material removal is highest there, resulting in highest percentage reduction in the strut diameter compared to the as-built condition.

The images (Figure 5) of the first layer of the lattice structures after PEP under different conditions show that the strut diameter in layer 1 has been reduced by more than 25% in all cases. This is due to the removal of partially melted powder particles from the lattice surface. The reduction in diameter under forced flow conditions is always greater than in normal PEP polishing. The results clearly show the significant contribution of electrolyte flow in improving the material removal rate. This is possibly due to the effective removal of the bubbles formed, which create a thin layer of vapour around the surface and thus improve material removal. The material removal is slightly higher at a flow rate of 4 l min^{-1}. It can also be seen from the image that the gloss on the struts is best at 4 l min^{-1}.

The evolution of the strut diameter in each layer of the lattice structure for different polishing conditions is shown in Figure 6. For the lattice structure polished without flow, the effective removal at the struts was the same at both open ends (layers 1 and 5) and lowest at the centre struts, as expected due to the lowest electrolyte access and bubble entrapment. For PEP with flow, the variations of the strut diameter are mostly in the same trend, except for the polished sample at 4 l min^{-1}, which showed a large consistency after the first layer of BCC cells.

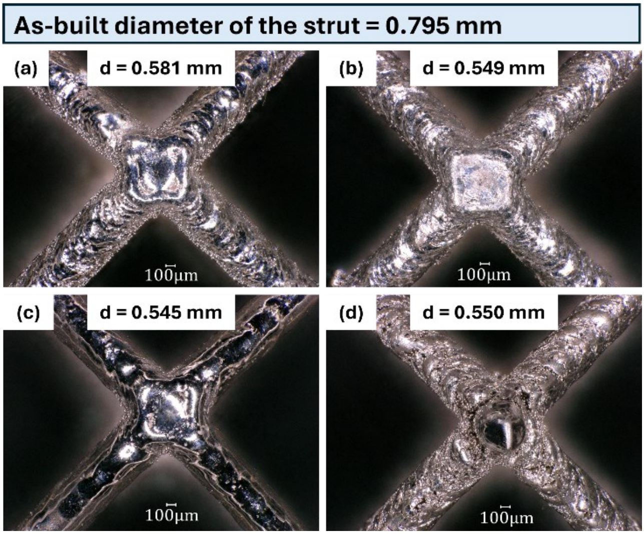

Figure 5: *Images of Layer 1 lattice struts after PEP polishing (a) without forced flow and with forced electrolyte flow rate (b) 2 l min^{-1}, (c) 4 l min^{-1}. and (d) 6 l min^{-1}*

The strut diameter in the case of PEP at 6 l min^{-1} is higher than that without flow from layer 2 to 5. This indicates that the effectiveness of polishing is not linear with the flow rate and optimisation of the flow rate based on the samples is required. This could be due to the high turbulence of the higher flow rate disrupting the vapour gas envelope and effectively preventing continuous PEP polishing.

The results suggest that a flow rate of 4 l min^{-1} is best for the most uniform polishing under the current polishing conditions. The additional removal in layer 1 must be compensated for in the CAD model before printing. The deviation at different polishing times must be analysed to determine the trend and formulate the correction factor for the CAD model. The use of a custom nozzle led to more homogeneous polishing without the appearance of localized bright spots on the lattice surface.

The design of the nozzle can be further optimised by correlating the experimental results with flow simulations. The influence of changing the orientation of the lattices and introducing multiple nozzle systems still needs to be investigated. The possibility of rotating the lattices within the electrolyte tank can also lead to more uniform strut diameter after PEP.

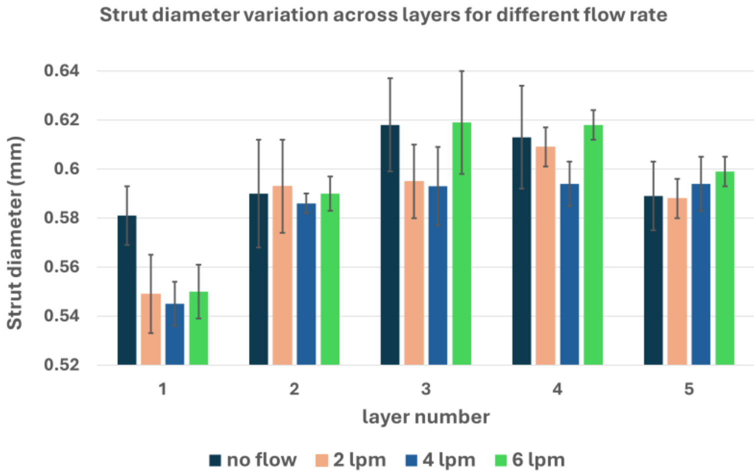

Figure 6: *Plot showing lattice strut diameter across the lattice layer after PEP under different conditions*

4 Conclusion

Lattice structures with BCC patterns were polished by varying the flow rate of electrolyte solutions to investigate the influence of the flow rate on the achievable polishing depth in this type of structures.

The results show that the best polish is achieved with a forced electrolyte flow of 4 l min^{-1}. Increasing the flow rate did not result in better material removal. Higher flow rates assumably lead to disruption of the vapour-gaseous envelope, which is important for PEP. These experiments show the importance of electrolyte flow when polishing complex structures with cavities. Further experiments need to be conducted to determine the compensation factor for dimensional deviations after polishing.

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