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Plasma electrolytic polishing of additively manufactured lattice structures: influence of cell size and forced electrolyte flow

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Abstract

Plasma electrolytic polishing (PEP) has proven to be an effective surface finishing technique for complex additively manufactured (AM) components due to its ability to process intricate geometries. This capability makes PEP particularly suitable for lattice structures, which are widely used in aerospace and biomedical applications due to their favourable strength-to-weight ratio. However, ensuring uniform polishing of both the outer and inner surfaces, especially for high density lattices, remains a challenge. In this study, SS316L lattice structures with different cell sizes affecting their overall density were polished with PEP under two conditions: with and without forced electrolyte flow. An external nozzle system was used to direct the forced flow and improve the penetration of the electrolyte into the inner regions of the lattice structures. The effectiveness of the polishing process was evaluated by cross-sectional analysis and optical microscopy, focusing on surface integrity and polishing penetration depth. The combination of PEP with forced electrolyte flow improved effective material removal and surface smoothing. The results also showed the potential to polish deeper inside the denser lattice struts with forced electrolyte flow. The results highlight the importance of optimizing electrolyte flow conditions to achieve consistent surface finishes in geometrically complex structures. This study provides valuable insight into improving the surface integrity of lattice structures in advanced industrial applications that require precise surface finishing.

Keywords: Plasma electrolytic polishing, additive manufacturing, lattice structures, surface integrity

1. Introduction

Additive manufacturing (AM) has become one of the leading manufacturing techniques for producing complex parts due to its design flexibility and ease of execution. With extensive research into additive manufacturing, more and more applications are being explored and utilized for complex structures that would otherwise be very difficult to manufacture. Lightweight materials offer a high strength-to-weight ratio and great design freedom. These properties are preferred and in demand due to the requirements of the automotive, aerospace and energy industries. Lattice structures are among those that meet the requirements of lightweight materials and can be adapted for specific applications depending on the strength-to-weight ratio [1].

The exploration of various fabrication technologies to produce metal lattice structures has been reported [2], but in the current AM context, both laser and electron powder bed fusion (PBF-LB/EB) are the most promising methods of choice. PBF-LB has become widely used due to its ability to produce complex metallic structures and the ability to work with different types of metals [3], whereas PBF-EB is still not widely used. In the PBF process, layers of metal powders are sequentially melted to create the final object. The finished part can be characterized by sintered or partially melted powder areas. The occurrence of random pores and defects in the finished object due to powder residues or other uncontrollable factors in the process is unavoidable. The lattice structures produced with the PBF process often have a surface roughness, as shown in Figure 1, which can be considered too high for many applications. The high surface roughness also has adverse effects on mechanical and corrosion properties.

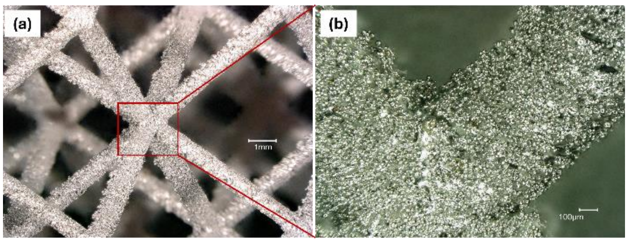

Figure 1: a) Lattice structure produced by PBF-LB/M and b) detail of surface finish and imperfections in lattice struts

Post processing has become an integral part of AM workflow. Abrasive polishing, chemical and electrochemical polishing are usually used to improve the surface quality of these lattice structures with complicated geometries. Abrasive polishing proves to be difficult, mainly because areas close to the surface and corners are prone to increased wear and internal stresses can arise due to plastic deformation. Later processes use harmful chemicals and produce harmful gases during polishing, which makes them less sustainable[4].

Plasma electrolytic polishing (PEP) is a relatively new technology that is suitable for improving the surface integrity of 3D printed metal parts. PEP, a form of anodic dissolution, achieves surface levelling through electrochemical and plasma reactions [5]. In addition, PEP improves surface integrity without harmful chemical additives as in chemical or electrochemical polishing, due to the physical and chemical interactions of the plasma that forms around the polished part. PEP appears to be a promising

environmentally friendly technique for the post-processing of additively manufactured lattice structures.
Figure 2 shows a standard configuration for the PEP process. In this process, the workpiece to be polished is anodically polarised and immersed in a suitable aqueous electrolyte solution. In addition, a cathode electrode is immersed in the electrolyte bath, the geometry of which does not have to match that of the workpiece, but it is important that the surface ratio between anode and cathode does not exceed 1:10. This ratio is crucial to facilitate the formation of a plasma layer on the surface of the polishing sample [6].

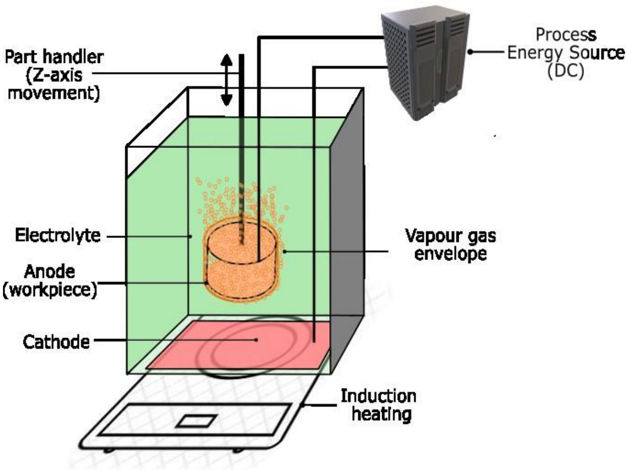

Figure 2: A standard PEP setup

The feasibility of PeP for the post-processing of AM fabricated lattice structures is less explored [6], [7]. The inclusion of forced electrolyte movement within the tank to improve the polishing efficiency for lattices has not yet been investigated. Therefore, this study investigates the influence of PEP on improving the surface properties of AM lattice structures. Body-centred cubic (BCC) lattice structures with different relative densities are investigated under PEP polishing with and without forced flow in the electrolyte tank.

2. Materials and methods

Lattice structures made of SS316L material produced using laser powder bed fusion technology were used for the polishing tests. Cubic blocks of side 25 mm with BCC unit cells with a strut diameter of 0.5 mm were chosen for the study. The relative density of the lattice was varied by varying the number of unit cells (smallest repeating units) in the cube. This was achieved by changing the number of unit cells along the edge of the cube from 3 to 9 (Figure 3).

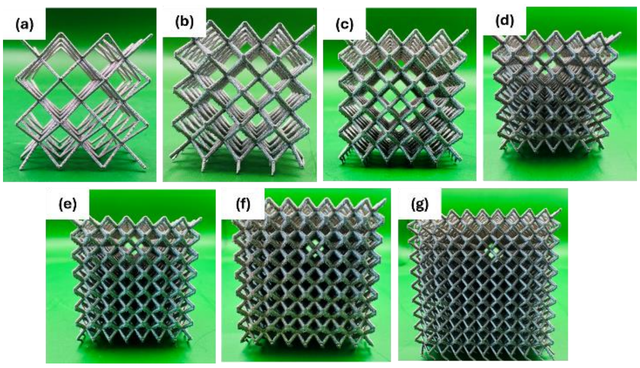

Figure 3: Lattice structures in as-built conditions with varying number of unit cells along the edges (a)3, (b) 4, (c) 5, (d) 6, (e)7, (f)8 and (d) 9.

Table 1 shows how the samples are named and how they are referred to in the rest of the article based on their different relative density (ratio of the density of the lattice structure to a solid block of the same dimensions).

Table 1 : Samples for polishing

Sample name	Number of unit cells along the edge	Relative density (%)
Sample 1	3	1,57
Sample 2	4	2,77
Sample 3	5	3,27
Sample 4	6	6,17
Sample 5	7	8,34
Sample 6	8	10,83
Sample 7	9	13,62

PEP was performed in a 0.33M ammonium sulphate solution maintained at 75°C and 320 V process voltage. Each sample was polished for 3 minutes under normal polishing conditions and with an additional forced electrolyte flow of 2 lpm over the lattice structures, as shown in Figure 4.
The samples before and after PEP were characterised using a Keyence VHX 7000 series optical microscope.

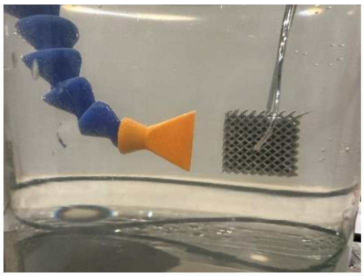

Figure 4: Representation of forced flow setup for polishing lattice structures. (actual experiments were carried out in steel tank)

3. Results and discussions

The microscopic images of the first cell layer from outside of the lattice blocks before and after PEP are shown in Figure 5. The cells are chosen in such a way that it is from the side facing the nozzle in case of forced electrolyte flow polishing and the from the bottom side in the immersed position in case of normal PEP conditions. These images were selected to show the trend as the densities are increased from the lowest to the highest value. The images revealed that the diameter of the lattice struts of lower density lattices (samples 1-3) has varied from the initial CAD more compared to the denser lattices. This could be due to the higher tendency for adhesion of partially molten powder because of poor heat transfer. The images clearly show that for the outer layer, partially fused powder particles adhering to the lattice struts were mostly removed after PEP both under normal polishing conditions and with forced electrolyte flow. It can also be seen that for lattice structures 1-3 with smaller relative density (bigger cell size), the thickness of the struts is significantly reduced after PEP compared to samples 4-7. Even with low relative density lattices, the forced flow further increased material removal, at least in the outermost layer of lattice struts.
It is assumed that these variations are due to the improved removal of gas bubbles that form inside the lattice during polishing. In the case of normal polishing by immersion, the fresh electrolytes can only reach the inside of the complicated

lattice structures to a limited extent, which reduces or restricts the polishing capacities. The external forced flow brings fresh electrolyte to the surface and improves the electrochemical side of polishing together with the forced removal of bubbles trapped in the lattice structures.

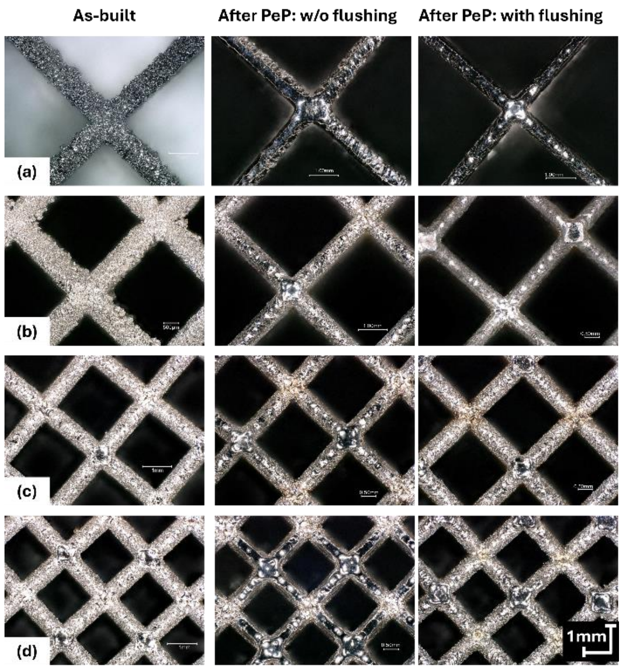

Figure 5: Microscope images showing strut thickness variations before and after PEP for (a) sample1, (b) sample 3, (c) sample 5 and (d) sample 7.

Another aspect that investigated was the depth of polishing within the lattice structures under normal and electrolyte flushing conditions. Figure 6 shows the images of lattice cells in different inner layers of the lattice samples 1 and 3. The images clearly show the difference between the outermost lattice cells and the inner cells.

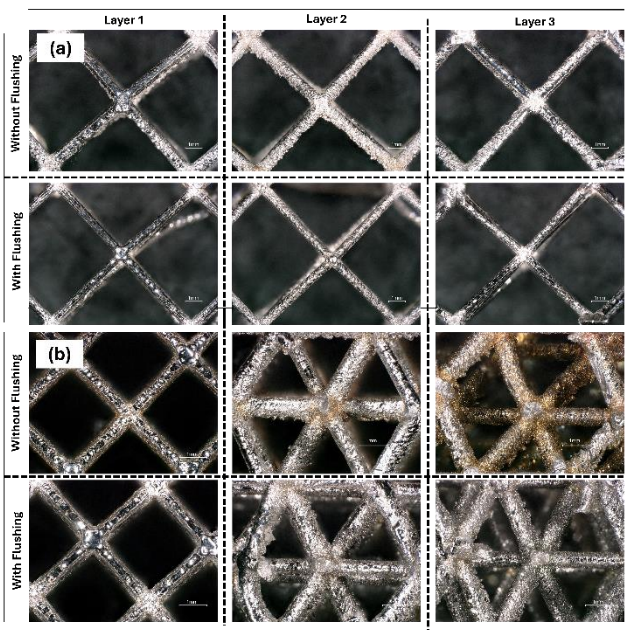

Figure 6: Images showing the effectiveness of PEP under both normal and forced flushing conditions for lattice structures with cell density along the edges as (a) 3 and (b) 5.

With increasing depth, the influence of polishing decreases under both polishing conditions. However, there is a slight improvement when using forced electrolyte flow and the struts are shinier than before. For lattice structure with biggest cell size considered (relative density 1.57%) (Figure 3a), PEP was also effective in the interior, regardless of using flushing or not. With flushing, there is a slight improvement in gloss and surface quality. This is a clear indication of the improvement on the surface quality inside the lattice structures. However, further investigations with different electrolyte flow rates should be carried out to be sure on what maximum polishing depth can be achieved.

With PEP, the formation and movement of gas bubbles is of great importance for the uniformity of polishing. This emphasises the importance of orienting the samples during polishing. This can also be seen in Figure 7, where different sides of the lattice structures are polished to different degrees. This suggests that further investigation by changing the orientation of the samples between polishing operations could improve the uniformity of polishing. A comparative analysis of PEP with and without forced electrolyte flow shows that the lattices polished with flushing has better uniformity than that polished under normal conditions. This indicates that the results can be further improved with higher flow rates and more nozzles pointing in different directions.

Figure 8 illustrates lattice structures with localized areas that are more polished. These are located at the point where the forced flow impacts on the lattice structures. This shows that the size and strength of the flow stream also influence the polishing efficiency. These markings are limited to the outermost layer and further sections do not show similar patterns at depth.

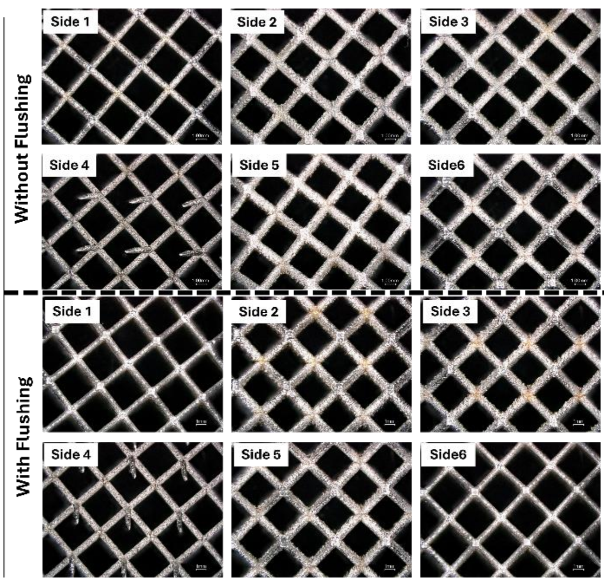

Figure 7: PEP influence on different sides of lattice structures (cell density 5 along edges) under normal polishing conditions and with forced flushing

This could be because the flow loses its shape and force as soon as it is obstructed by the outer layer. For further investigation, the flow needs to be reshaped to include the entire lattice within

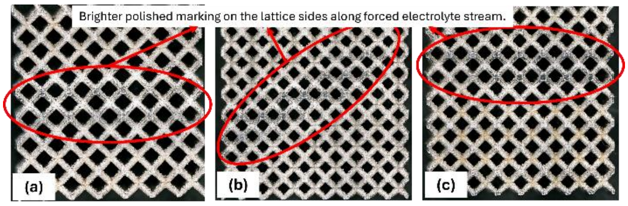

Figure 8: Lattice structures with localized areas that are more polished due to forced flow streams.

the stream to determine the effects of flow shape on surface quality. In addition, polishing at a much higher flow rate could improve penetration into samples with higher relative density.

4. Conclusions

BCC lattice structures with different densities were polished with PEP to investigate the influence of surface quality and polishing depth in normal immersion and in PEP with forced electrolyte flow conditions.

The results indicate that the normal immersion based polishing technique can be used when the relative density of structures are very less facilitating easy access for the electrolyte to inner struts. Its effectiveness to penetrate deep into the lattice structures is limited with increasing relative density and accordingly the ease with which the bubbles can escape is reduced. With forced electrolyte flow using an additional nozzle system inside the electrolyte tank, the trend is the same, but it has a greater reach towards the inner struts than the normal PEP technique.

With forced electrolyte flow, the results indicate the importance of flow rate and flow direction, as the flow left localised bright spots on the lattice block. This preliminary study shows opportunities for further optimization and investigation related to electrolyte flow.

The material removal on the different sides of the lattice structures varied depending on the orientation of the sample in the electrolyte tank. This is mainly due to the influence of bubble formation and removal at different sections of the lattices, which reduced the availability of fresh electrolyte at the part surface.

Although the trend is visible, the polishing effects are not satisfactory and require further investigation to find the optimal flushing conditions.

This study shows the potential of PEP as a polishing method for complex lattice structures with promising results, indicating possibilities to achieve suitable parameters with further studies.

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