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Multiscale post-processing of metal additive manufactured parts by electro-polishing technology

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Abstract

Additive Manufacturing (AM) is introduced world-wide, enabling fabrication of complex 3D structures, resulting in game-changing manufacturing concepts. Although AM technology is revolutionizing aerospace and biomedical device industries, obtaining good surface quality still represents a major challenge. Due to its excellent properties, titanium alloys like Ti-6Al-4V are mostly used in these applications for AM. Electrochemical polishing (EP) can be an interesting solution as post-process for these metal AM parts.

In the presented study, EP was performed on AM parts with different geometries and materials (Titanium alloy Ti6Al4V, Aluminium alloy AlSi10Mg and stainless steel EOS PH1). The effect of polishing settings with pulse technology is investigated and it is shown that EP with pulse technology eliminates surface asperities effectively. Surface roughness from micron to sub-micron range could be obtained, for Ti-alloy (initial: Ra = 1.4 µm and Rz = 11.1 µm, after EP: Ra = 0.07 µm and Rz = 0.5 µm), for stainless steel (initial: Ra = 4.4 µm and Rz = 30.0 µm, after EP: Ra = 0.55 µm and Rz = 5.1 µm), and for Al-alloy (initial Ra 1.68 µm and Rz 8.97 µm, after EP Ra 0.67 µm and Rz 3.08 µm).

Post-processing, electrochemical polishing, additive manufacturing, metal, surface engineering

1. Introduction

Advances in Additive Manufacturing (AM) allow for high resolution fabrication of complex 3D structures. This enables the construction of tailored workpieces with virtually any shape. As promising AM applications can be mentioned the development of lattices for orthopaedic bone implants [1], cooling channels inside moulds for casting and lightweight parts for the aerospace industry [2].

Because of its bio-inertness, high strength and corrosion resistance, Ti6Al4V is an appealing material for AM parts, in particular for constructing orthopaedic devices [4] and for aerospace applications [2]. Other common used materials in metal AM are stainless steel and aluminium. However, when using metal AM technologies such as Direct Metal Laser Sintering (DMLS) or Electron Beam Melting (EBM), undesired semi-melted beads are attached to the workpiece. These beads generally range from 10-45 microns for DMLS and from 45-106 microns for EBM. They jeopardize geometrical accuracy, mechanical properties and influence behaviour of the parts in the applications. The cleaning of the metal AM fabricated metal parts is another challenging task, due to its complex geometry.

Among other technologies (e.g. plasma polishing – *Plasotec*) electrochemical polishing (EP) provides an interesting approach as post-process to control the reduction of semi-melted beads and assure the parts to be particle free. This helps to ensure that the manufactured part is identical to the designed structure. EP can handle complex geometries and can also be used for the formation of micro and nano-roughness on the part surface, which is important for implant parts [4].

In EP process, mass transport controlled dissolution results in surface smoothing [5]. Multiple parts with complex geometry can concurrently be polished. Preliminary results show the potential to use electrochemical pulse technology polishing to eliminate surface asperities effectively and these results are discussed in the subsequent paragraph. The last part details the conclusions of the EP study.

2. Principles and Methodology

EP is an electrochemical process for shaping and surface structuring of metals by controlled anodic dissolution:

$$Me(s) \rightarrow Me^{+n} + ne^{-}$$

Here, the workpiece is employed as working electrode (WE) and then immersed in electrolyte [5] as depicted in figure 1.

In EP two effects are achieved: levelling and the brightening effect. Mass transport controlled dissolution results in surface smoothening (levelling effect). Further, the difference in grain orientation plays no role resulting in a random removal of atoms leading to a very smooth surface (brightening effect).

The levelling effect is controlled by the Nernst diffusion layer.

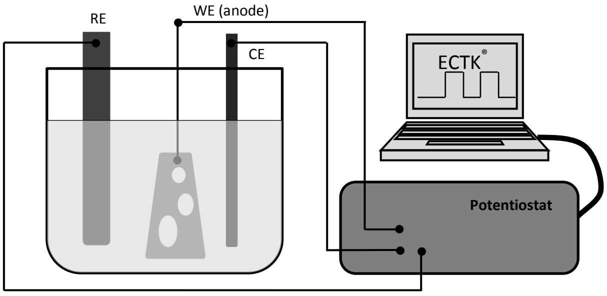

Figure 1. Experimental electro-polishing setup.

Surface structures larger than the Nernst diffusion layer are called macroprofiles whereas smaller ones are called microprofiles. EP acts only on microprofiles. Conventional EP methods cannot directly be applied to titanium parts and its alloys, as in the standard aqueous acidic environment EP is limited by the formation of TiO_2, which stops the removal process [5]. Low conductive, water-free electrolytes are required to affect the primary current distribution such that the voltage gradient between the asperities and the recesses of the surface is magnified and these are preferentially removed [6]. Moreover, standard EP methods are designed for surface finishing of parts with much lower initial surface roughness than the one achieved with AM for Ti alloy parts (Ra about 1-150 µm). The following strategy, first developed by the group of Landolt [7], will be adapted to address this problem [8].

It is well known that the Nernst diffusion layer can be controlled by pulsed current. For very short pulses the diffusion layer is very thin as not enough time passes to allow the layer to fully develop. Consequently, when EP with very short pulses is used, macroprofiles can be converted to microprofiles by forcing the diffusion layer to follow the surface. It becomes possible to apply EP to surfaces having a roughness higher than the typical Nernst diffusion layer (50 µm -100 µm). In a first step, by using very short pulses (0.1 µs to 100 µs) large asperities (>100 µm) are reduced in height, whereas smaller (smaller than the diffusion layer) are reduced uniformly without any significant smoothening effect. Once the large asperities have become micro-profiles, the pulse duration is increased in order to further smooth the surface.

In the presented study a solution of ethylene glycol and 0.9 molar NaCl and an Ag|AgCl reference electrode was used.

EP was performed on AM parts with different geometries and materials: Titanium alloys Ti6Al4V, Aluminium alloy AlSi10Mg and stainless steel EOS PH1. Polishing results were analysed qualitatively by microscopy and quantitatively by a mechanical profilometer (*Mitutoyo SJ-210*) to show the feasibility of this approach on metal AM parts. The influences of polishing settings with pulse technology like duty cycle, voltage amplitudes, pulse width and polishing time were investigated quantitatively by laser profilometer on a Ti alloy test sample with initial arithmetic mean surface roughness of Sa = 15 µm.

3. Experimental results

Effect on the surface roughness of the investigated different parameter settings for EP with pulse technology on a standard Ti alloy sample (a small square plate) is summarized in figure 2.

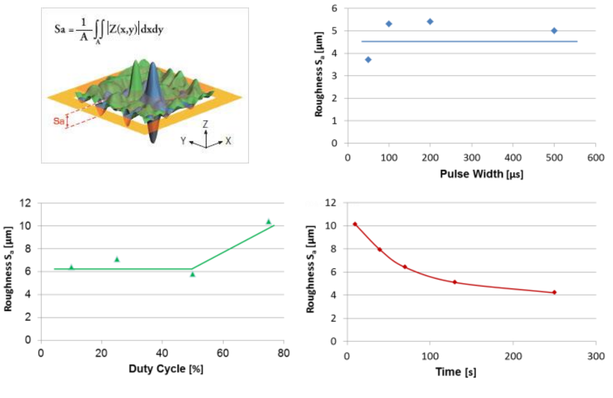

Figure 2. Effect of pulse width, duty cycle and time of the EP process on the arithmetic mean surface roughness Sa of an Ti alloy sample with initial roughness of Sa = 15 µm.

The AM fabricated Ti alloy structure was electro-polished with the following parameters: high pulse = 15 V, low pulse = 2.5 V, duty cycle = 20 %, pulse width = 200 µs, EP time = 35 min. The original average diameter of the beads is 20 µm. The semi-melted beads can clearly be observed in figure 3. These beads are greatly reduced and a smooth surface is achieved after EP treatment.

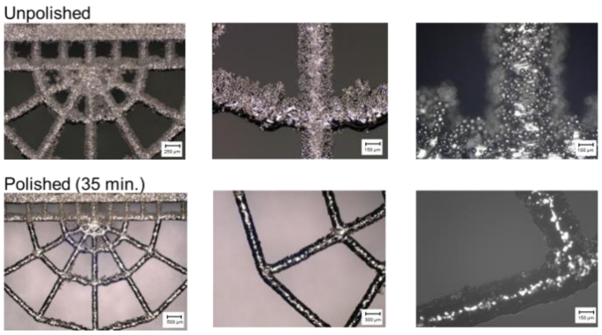

Figure 3. AM fabricated Ti6Al4V structure unpolished (attached semi-melted beads) and after 35 min. polishing (bead removal).

Figure 4 presents the results of EP on different AM fabricated steel parts. The difference in surface roughness can be observed, showing smooth surfaces after EP process.

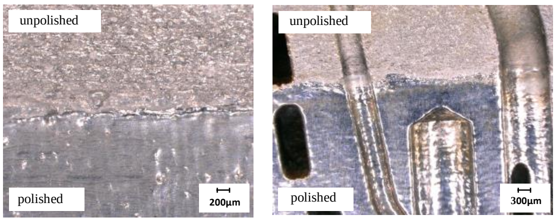

Figure 4. Effect of EP on AM fabricated stainless steel (EOS PH1) parts and maraging steel (MS1). Right: cross section of moulding part with cooling channels.

Results of the quantitative analysis of the roughness values before and after EP of different AM materials parts are summarized in figure 5.

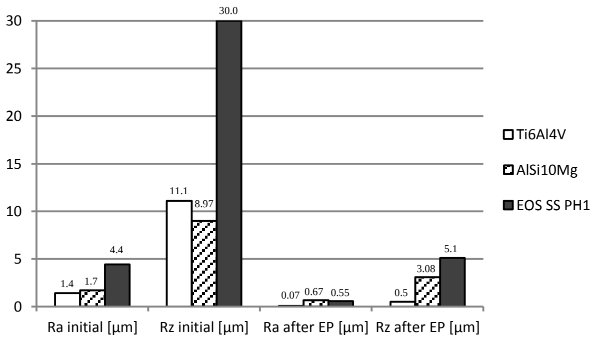

Figure 5. Roughness values of different materials before and after EP

4. Conclusions

EP using pulse technology together with ethylene glycol+NaCl electrolytic solution is an effective tool to eliminate surface asperities on AM parts of most common materials. Surface roughness from micron to sub-micron range could be easily obtained. Semi-melted beads attached on AM parts are greatly reduced and a smooth surface is achieved.

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