

Reducing Surface Roughness of Selective Laser Melting of 316 Stainless Steel Component by Electropolishing

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Abstract. Additive manufacturing (AM) is widely used in the fields of aerospace, automotive, and biomedical. Because it enables to fabricate and customize parts with complex geometrical features. However, due to the layer-by-layer deposition and the partially fused raw material, AM part suffers from the step and balling effects, which shows inadequate and poor surface quality. Conventional polishing methods such as grinding, milling, and sandblasting have been applied to meet the requirement of well surface quality. But these contact polishing techniques usually introduce extra residual stress and surface damage, which are unsuitable for workpieces with complex shapes. In this study, we propose an environmentally friendly electrochemical polishing method for AM 316L stainless steel parts based on a combination of positive and negative pulses. Unlike the traditional phosphoric acid or sulfuric acid electrochemical polishing liquid system, the sodium chloride electrolyte adopted in this study avoids the pollution problem of waste liquid. A negative pulse was introduced to avoid the impaction of Cl⁻ ions to the passivation film generated during the electrochemical polishing process. The effects of voltage, polishing duration, temperature, and duty cycle were analyzed by orthogonal experiments. Under the optimum reaction conditions, a surface roughness Ra of 0.421μm without pitting corrosion is achieved and the balling effect was eliminated.

Keywords:Additive manufacturing, Electrochemical polishing, negative pulse.

1. Introduction

Additive manufacturing (AM), also known as "3D printing", is a layer-by-layer manufacturing technique that allows the fabrication of high flexibility components without the restriction by the complex shape [1, 2]. Due to its well corrosion resistance and good mechanical properties, 316L stainless steel is one of the most widely used metal AM parts. It has extraordinary application potential in automobile, dies, and aerospace fields [3-6]. Selective Laser Melting (SLM), the most popular AM method, enables the production of complex solid components.

However, the surface of AM metal workpieces suffers from the "step effect [7]", "balling effect [8]", and "Powder adhesion [9]". The initial surface roughness Ra of the SLM part is 10~50μm, which cannot meet stringent requirements for the expected surface quality in aerospace or medical equipment, while the traditional mechanicals can reach 2.5μm or less [10].

Electrochemical polishing (ECP) is a promising process to reduce surface roughness. As for a non-contact polishing technique, ECP does not introduce undesired surface and sub-surface damage compared with mechanical polishing. Furthermore, the heat and reaction products can be taken away in time. ECP can be applied to workpieces with complex shapes.

In recent years, quite a few studies have focused on the ECP of 316L AM Parts. P. Rodriguez et al. [11] adapted a micro-positioning system to set the interelectrode gap to the optimum value. This ECP process achieves surface roughness Ra values ranging from 12 μm to about 3 μm. A.A. Gomez-Gallegos et al. [12] evaluated the effect of different parameters on surface quality by varying machining parameters such as voltage, interelectrode gap, electrolyte inlet temperature, and electrolyte flow rate. C. Rotty et al. [13] and K. Alrbaey et al. [14] develop an environmentally

friendly ECP process for 316L AM parts in deep eutectic solvents (choline chloride-ethylene glycol mixture) electrolyte.

Most ECP processes use an acidic electrolysis bath system, which is harmful to the ecosystem. This study proposes a sodium chloride electrolyte ECP system to treat SLM 316L stainless steel workpieces, which is an environmentally friendly process. In order to eliminate the penetration of Cl⁻ ions to the passivation film, a combination of positive and negative pulses are used instead of the traditional pulse shape of voltage. The factors including voltage, polishing duration, temperature, and duty cycle were investigated by the orthogonal experiment method, and the mechanism was analyzed. Under the optimum reaction conditions, the 316L AM workpiece was polished from a surface roughness Ra of 7.215μm to 0.421μm without pitting corrosion and the balling effect was eliminated.

2. Principle of Electrochemical Polishing

ECP is a method that uses the principle of electrochemical anodic corrosion to remove the residual surface inhomogeneity to reduce surface roughness and improve surface brightness. In the ECP process, both electrodes are immersed in the electrolyte simultaneously, and the anode surface is selectively dissolved under the activity of an electric current, thus developing the surface treatment of the workpiece. For the principle of ECP, researchers from all over the world have many disputes. At present, the mainstream theory of electrochemical polishing is the passivation film theory. According to the theory, a passivation film, as known as the viscous layer is formed and adsorbed on the workpiece surface in the ECP process. The highest point of the protrusion film is thinner than the depression film due to its more robust ability to diffuse into the electrolyte. Nonetheless, this kind of film has a more significant impedance. The dissolution rate of the convex part is higher than that of the concave part because the current density of the convex part of the workpiece surface is higher. The greater the difference in film thickness between the depressions and the projections, the greater the difference in current density. With the progress of polishing, the high points of the workpiece surface are gradually eliminated, the thickness of the passivation film changes, and the rough surface is progressively smooth.

Faraday's law is the basic principle followed in the ECP process. It expresses the relationship between the amount of substances involved in the redox reaction and the amount of charge at the electrode-solution interface. Faraday's law could be formulated as:

$$M = kQ = kIt \quad (1)$$

Where M, k, Q, I, t denote the mass of anode dissolved metal, the mass electrochemical equivalent, the electricity through the intersecting surface, the current intensity, and the time of current conveyance, respectively.

When the volume electrochemical equivalent is introduced, therefore,

$$V = \frac{W}{\rho} = \frac{kIt}{\rho} = \omega It \quad (2)$$

Where V, ρ, W, ω denote the volume, the density, the amount of substances involved in the reaction, and the volume electrochemical equivalent, respectively. Then the dissolution rate can be deduced as followed:

$$v = \frac{V}{S_t} = \frac{\omega I}{S} = \omega i \quad (3)$$

Where S, i denote the processing area and the current density, respectively.

It can be concluded that the removal speed depends on the volume electrochemical equivalent and current density

from (3). Volume electrochemical equivalent is determined by the material type and content of the anode. Current density is an essential parameter to evaluate the result of ECP, which is affected by several factors including voltage, pulse interval, duty cycle, electrolyte concentration, etc. Based on this idea, this study investigated the main factors in the ECP process. Additionally, the surface

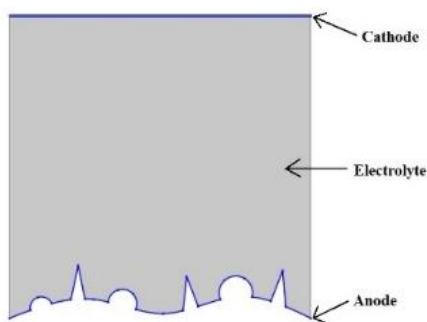
roughness is considered as the reference standard and the optimum reaction condition is obtained by varying parameters.

3. Simulation of Electrochemical Polishing process

Simulation of the ECP process was performed using COMSOL Multiphysics 5.5 (COMSOL, Inc.). The electrochemical corrosion module is adopted which coupling the deformation geometry with the second current distribution. In the simulation, it was considered that the electrolyte flow is electroneutral, homogeneous (the composition variations in the electrolyte are negligible), incompressible and the influence of electrode kinetics was included.

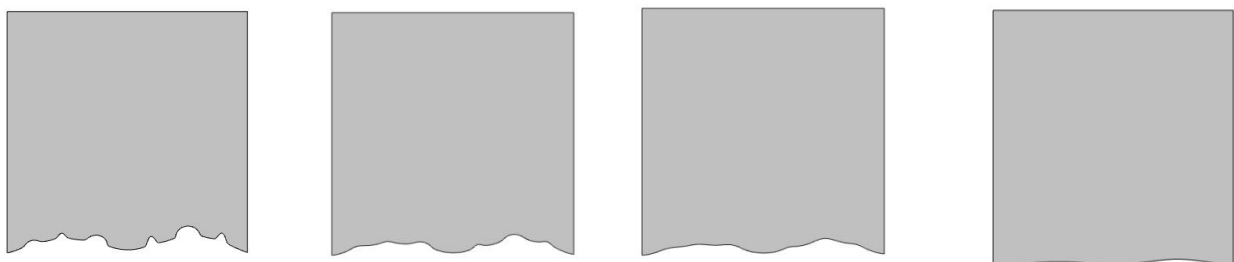
As shown in Fig. 1, a rough surface was provided, and the incomplete melt particles represent the balling effect in AM process. The surface of the deformed electrode has only the anode boundary, and the non-deformed boundary was the rest of the surface.

Boundary condition of COMSOL simulation



The anode electrode was 316L stainless steel, and the cathode was silver. The electrolyte was considered a solution of sodium chloride (NaCl). The polishing voltage was 1 V, the electrode gap was 10 mm, and the temperature was 25 °C. The cathode and anode boundary was set as the fluid inlet and fluid outlet, respectively.

In Fig. 2 (a), little amount of bulge on the anode surface has been removed in 400s. When the polishing time reached the 800s, as shown in Fig. 2 (b), the bulge on the anode surface was almost removed. However, the surface was still uneven. After 1200s, as shown in Fig. 2 (c), the bulge on the anode surface has been totally removed, but the surface was still rough. The reaction continued to make the surface smooth. When it reached 3000s, the surface was almost even, and it was obvious that the balling effect is eliminated in Fig. 2 (d). According to the simulation results, the



polishing of the AM workpiece could be summarized as eliminating the balling effect followed by the macroscopic leveling.

(a) (b) (c) (d)

Fig. 2. Time-dependent polishing profiles of COMSOL simulation. (a) After 400s; (b) After 800s; (c) After 1200s; (d) After 3000s;

4. Experimental Method

4.1 Preperation of Sample

In this study, 316L stainless steel workpieces were manufactured by the SLM process. As shown in Fig. 3, cuboid samples were designed with a dimension of $10 \times 10 \times 1$ mm (L \times W \times H) as the polishing area. The part bordering the workpiece was responsible for clamping on the electrode. The initial surface roughness Ra value was 7-10 μ m. The clean surface before the experiment was obtained through ultrasonic cleaning with ethanol, followed by washing with deionized

(DI) water.

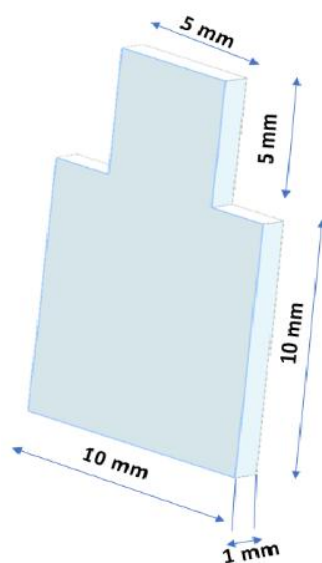


Fig. 3. 316L stainless steel workpiece model in CAD

4.2 Selection of Electrolyte

The combination of sulfuric corrosive, phosphoric corrosive, and a few different testing agents has been broadly utilized as the electrolyte concentration. The electrolyte containing sulfuric acid can obtain a smooth surface in 316L stainless steel under electropolishing; However, the solid corrosive utilized is harmful to the ecosystem. Its stable destructive properties are likewise hurtful to operators, effectively damaging laboratory equipment. According to previous experiments and studies, 7% NaCl was employed as an electrolyte.

4.3 Electropolishing process

The ECP process was performed in a conventional three-electrode cell which consists of an anode(316L stainless steel sample),a cathode (platinum), and a reference electrode(silver). A cathode was present adjacent to the portion of the work that requires electropolishing.

The application potential was provided by the CHI760E electrochemical workstation shown in Fig. 4. A hot plate agitator was adopted to heat the electrolyte, and a heat sensor controlled the temperature of the electrolyte. A magnetic stirring rod was used to stir electrolytes. The interelectrode gap width between the anodes and the counter electrode was set to 10 mm.

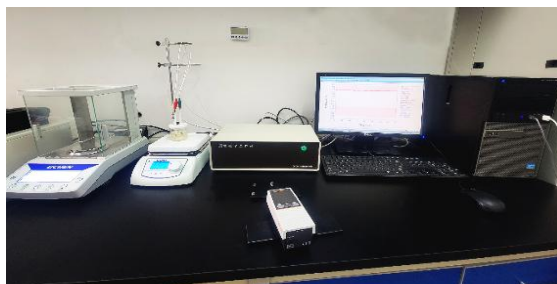


Fig. 4. Setups in the Electropolishing process

The principle of pulsed ECP is to periodically switch the power supply rather than work continuously so that the anode dissolves when the workpiece is powered on and remains neutral when it is powered off. During the pulse interval, the electrolysis products and reaction heat in the processing area can be fully discharged. When electricity is applied, hydrogen deposited on the surface of the cathode generates a pressure wave that promotes the flow of the electrolyte, which is beneficial to obtain a stable and ideal surface. Many studies mentioned that the Cl^- ions could impact the passivation film and cause massive pitting corrosion. The pulse voltage is a combination of positive and negative instead of the conventional pulse shape. According to the LSV curve, the pre-tests show that the positive voltage is suitable between 4-6V, and the negative voltage is suitable around -0.5V. During the negative pulse, the polarity of the tool electrode and the workpiece changes, which switches the direction of the electric field and restricts the Cl^- ions entering the machining gap.

4.4 Characterization techniques

An Olympus LEXT OLS4100 confocal laser scanning microscope and a MV3000 digital microscope are employed to investigate the impact of electropolishing on the surface properties. The R_a parameter was used for the quantitative analysis. The surface evaluation was repeated four times at each location in both directions, parallel and perpendicular to the edge of the workpiece. The evaluation length was $640 \mu\text{m}$ and the magnification of the objective lens was x20.

4.5 Orthogonal array design

The main processing parameters of ECP, including the working voltage, polishing duration, duty cycle, and temperature, were selected as orthogonal experimental factors. An orthogonal table of $L_9(3^4)$ (four factors and three levels) was designed, and the levels of the factors were equidistant, as shown in Table I. The R_a value was taken as the index for evaluating surface roughness, and the results were then analyzed with variance analysis.

Table I. Factors and levels of orthogonal array design

Levels	Factors			
	Voltage (V)	Polish duration (min)	Temperature($^{\circ}\text{C}$)	Duty cycle(%)
1	4	3	25	20
2	5	4	35	30
3	6	5	45	40

5. Results and discussion

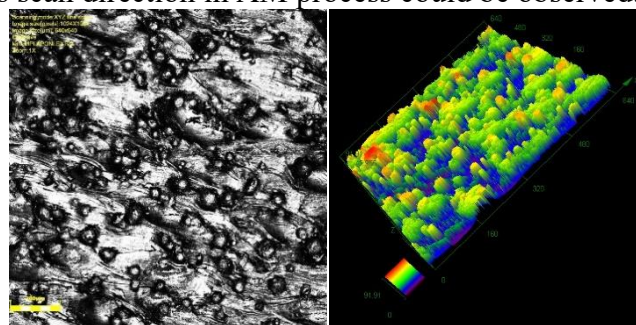
The analysis of variance from Table II. shows that voltage and temperature are the main factors in this experiment, which significantly outweigh the time and duty cycle. In this part, we focus on the influence mechanism of voltage and temperature during the ECP process.

Test	Voltage	Polish duration	Temperature	Duty cycle	Surface Roughness Ra(μ m)
1	1	1	1	1	0.587
2	1	2	2	2	0.421
3	1	3	3	3	0.663
4	2	1	2	3	0.514
5	2	2	3	1	0.509
6	2	3	1	2	0.685
7	3	1	3	2	0.734
8	3	2	1	3	0.689
9	3	3	2	1	1.076
K1	0.557	0.612	0.654	0.724	
K2	0.569	0.54	0.67	0.613	
K3	0.833	0.808	0.635	0.622	
R	0.276	0.268	0.035	0.111	

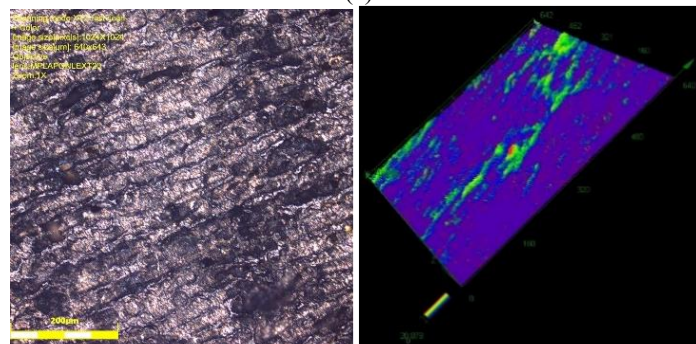
Table II. Orthogonal experimental results

The leveling effect is not obvious at low voltage(4V) and low temperature (25 °C). Low voltage leads to low current density, and the surface removal rate is lower than the generation rate of the passivation film. Due to the low temperature, the ion in the electrolyte is inactive, which is not conducive to the timely diffusion of anode reaction products.

The best or optimal polishing performance was found at a voltage and temperature of 5V and 35 °C , respectively. As the temperature of the electrolyte builds, the consistency of the solution diminishes, which enhances the convection and speeds up the dispersion rate. In addition, the convection of the solution facilitates the separation of the bubbles retained on the anode. The solution close to the anode could be quickly restored, which is beneficial to the dissolution of the anode and intensifies the diffusion of anode products. At this point, the current density reaches a steady state, and the formation rate of passivated film and dissolution rate attains equilibrium. As shown in Fig. 5, the balling effect formed by AM was significantly removed. Most insoluble particles were dissolved or removed, leaving a crater-like mark on the surface. In addition, processing traces such as scan direction in AM process could be observed.



(a)



(b)

Fig. 5. Surface profiles of original and processed by LEXT OLS4100. (a)Balling effect is visible on the original surface; (b)Balling effect is well eliminated.

The surface quality gradually deteriorates, and pitting corrosion is visible as the voltage or temperature continues to increase in Fig. 6. Two possibilities may explain this pitting phenomenon. On the one hand, as the voltage increases, the anode chemical reaction is intense, and the bubble generation far exceeds its diffusion, causing the accumulation of bubbles, thereby resulting in surface defects such as dots and spots. On the other hand, the increase in temperature impels the reactive ions from moving faster, resulting in the thinner of passivation film and the stronger activity of Cl^- ions, allowing them to easily penetrate the passivation film and form massively visible pitting corrosion on the surface.

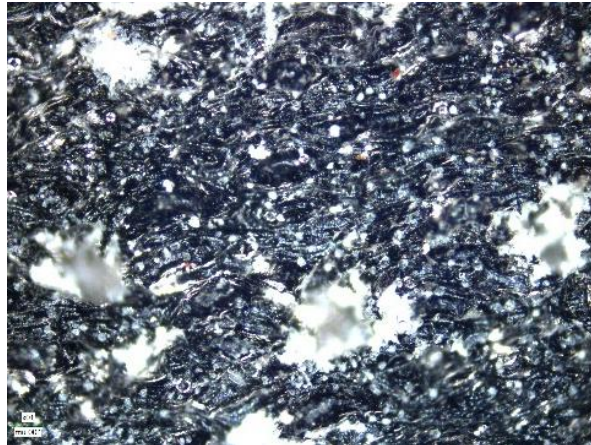


Fig. 6. Pitting corrosion(white pits) on the surface during ECP process by MV3000

Through experimental analysis, the voltage and temperature should be set within a reasonable interval to obtain an excellent surface. In this experiment, a voltage of 4V and a temperature of 35°C is a suitable choice. In addition, there might be an optimal value in a certain interval near them, which needs more experiments to verify. Although polishing time and duty cycle had little effect in this experiment, they might be important factors in other studies. In other words, the order of effect may be different from the experiments in other studies.

In addition, a combination of positive and negative pulses was adopted in this experiment to prevent Cl^- ion from impacting the passivation film. It was proved that the negative pulses indeed prevented the pitting corrosion caused by Cl^- ion compared with the results of other studies. During the negative pulse interval, the workpiece and the tool electrode are employed as the cathode and anode, respectively. The Cl^- ion trajectories around the sample were switched to avoid widening the concentration gradient and reducing the possibility of pitting corrosion. At the same time, for the whole electrolyte system, the existence of a negative pulse promotes the full exchange of ions and reaction products so that the electrolyte region around the sample is refreshed, thus improving the stability of processing.

6. Conclusions

In this study, an environmentally friendly ECP method for AM 316L stainless steel parts based on a combination of positive and negative pulses was proposed. The best or optimal polishing performance reached a surface roughness R_a of $0.421\ \mu\text{m}$ with the original surface roughness value $7.215\ \mu\text{m}$ was found at a voltage, temperature, polishing duration, and duty cycle of 5V, 35°C , 3mins, and 35%, respectively. Compared with the initial workpiece, the surface after treatment tends to be flat and eliminates the balling effect, which can also play a role in damage detection in manufacturing. The effects of voltage, temperature, polishing duration, and duty cycle are discussed in the paper. It is proved that voltage and temperature are vital factors in this experiment, and the removal mechanism was analyzed. The introduced negative pulse can greatly reduce the influence of Cl^- ion penetration impacting the passivation film, which brings about pitting corrosion and other

surface damage. Limited by the number of experimental samples, the surface quality may achieve better results with other parameters, which is also the focus of follow-up research. Pits due to the dropout of these particles adversely affect surface integrity and become a new target for polishing.

Acknowledgments

This work was financially supported by Beijing Institute of Technology Ben Yuan funding.

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