Theoretical and numerical researches on the electrochemical polishing of dental prostheses realized by selective laser melting

E Moraru¹, O Dontu¹, D Besnea¹-*, C Rizescu¹, D Rizescu¹ and V Constantin¹

¹ University Politehnica of Bucharest, Department of Mechatronics and Precision Mechanics, Splaiul Independenţei Street No. 313, Romania

E-mail: d_bes@yahoo.com

Abstract. The paper presents and describes an electrochemical finishing process - anodic polishing, which substantially improves the quality of dental prostheses realized by selective laser melting, obtaining prosthetic restorations with distinguished mechanical properties. The authors developed a theoretical model of electrochemical polishing, which was validated by a numerical simulation, obtaining very close results between the two models. After this analysis, it is possible to choose the proper polishing regime and the appropriate process parameters in order to obtain predetermined finishes for dental prostheses realized by selective laser melting.

1. Introduction

Additive technologies have opened the possibility of building a physical model starting directly from computer three-dimensional design [1, 2, 3, 4, 5]. These prototypes are being used in an increasingly progressive manner in various fields, especially in the field of medical prosthetics. In this area, the models are used for functional testing as well as sometimes as the final piece. Additive technologies are gaining more ground than conventional processes, with important strengths: generating complex geometries, early involvement of customers / patients in product development, saving time and money [3, 4, 5]. These techniques also have some special problems that deserve to be overcome in order to achieve the desired performance. The main issues include the poor quality of the resulting surfaces, so the post-processing steps are at least as important as printing the proper piece. In order to obtain the required specifications or to improve the properties such as surface quality, geometric accuracy and mechanical properties, it is often necessary to process and finish the components made with additive manufacturing techniques. The high quality of the products obtained by the additive material processes allows the use of many finishing techniques to meet the requirements of surface quality and geometry.

Generally, these processes become more valuable by improving equipment performance, improving the quality of the parts, but viable post-processing methods are also essential to improving the quality of the parts.

Surface roughness is a well-known imperfection shared by most additive technologies, especially those using metallic raw materials, which reduces fatigue resistance - the crucial feature of cyclical load components [2]. For this reason, a wide-ranging investigation must be made in order to be able to use the finite printed products in the most efficient way.
2. Material and methods
The present study focused on the analysis and investigation of the surface quality of dental prostheses realized with the use of metallic additive technologies - the process of selective laser melting. Selective laser melting (SLM) is a layer manufacturing process that allows the generation of 3D complex pieces by consolidating successive layers of the pulverized material over one another. Consolidation is achieved by processing selected areas using the thermal energy provided by a focused laser beam. With a beam deflection system (Galvano mirrors), each layer is scanned according to the corresponding cross-section of the CAD model. The execution of these prosthetic elements was performed on the Sysma MYSINT 100 laser selective melting equipment. The raw material for the restoration was the powder of the Co-Cr metal alloy with the following composition: Co 59%, Cr 25%, W 9.5%, Mo 3.5%, Si 1%, others <1%. These metal powders for realizing very complex restorations in the dental sector consist of high quality alloys and allow the production of dental prostheses with remarkable mass production performance through SLS / SLM systems [4,6,7]. Obtained dental prosthetic restorations as well as microscopic images with 40x magnification of these are presented in the figure 1.

![Image of dental prosthesis in rough and after manual finishing](image_url)

**Figure 1.** Dental prosthesis in rough (right) and after manual finishing (left).

Particles of impurities, surface irregularities and remaining material on the prosthesis are observed, which have been removed relatively by manual finishing. However, the external part is considered an important one and requires a suitable finish to be able to effectively adhere to the ceramic or polymeric coating material. Moreover, the interior part of the prosthesis is even more important because it comes in direct contact with the human tissues. Figure 1 shows that the quality of the finished surfaces leaves desirable and a more precise and fine post-processing operation is required in order to obtain the best biomedical and material properties. For this purpose, the next chapter introduces and analyzes the electrochemical polishing process, which can be used to obtain the desired surfaces of the prostheses.

3. Numerical simulation
This chapter presents an effective method for finishing dental prostheses made by laser selective deposition - electrochemical polishing. A theoretical analysis of electrolytic polishing and numerical analysis will be carried out with the results of simulation of the electro-chemical-mechanical phenomena occurring during the process. The purpose of this numerical analysis is to estimate how the prosthesis will be finished and to establish optimal process parameters for further experimental research.
During electrochemical polishing, the metallic part dissolves in the electrolyte, unlike electroplating / electrodeposition, where the metal ions moving through the electrolytic solution are deposited on the surface of the workpiece [8].

Electrochemical polishing is a well-known process in the metal finishing industry. This analysis illustrates the principle of electropolishing with the simplified geometry of the 2D model consisting of two electrodes (anode and cathode) and an electrolytic solution. The positive electrode has a protrusion or asperity of circular shape, representing a surface defect. The purpose of the study is to examine how this defect and the material around the electrode are removed in time. In addition, the behaviour of the structure will be analysed at the variation of the main working parameters.

The geometry of the circular asperity electrode that will be modelled in this chapter is represented in the figure 2 [9, 10]. The anode is represented by green, the electrolyte is blue, and the cathode is considered to be the lower part of the electrolyte in the figure.

![Figure 2. Schematic of the used model in the study](image)

The surface of the electrode is polished by removing the material from the local asperities in the selected areas, by immersing the nominal electrode in an electrolyte and applying a current. The rate of removal of the material \(v\) from the nominal surface of the positive electrode is proportional to the density of the normal current at the positive electrode surface, as shown in equation (1):

\[
v = -k \cdot J_n
\]

where \(k\) represents the electrochemical equivalent or coefficient of proportionality of the material, and \(J_n\) is the normal current density. The exact value of the proportionality constant \(k\) in physical applications is determined by electrode material, electrolyte, temperature, and other factors. In this case, the chemical equivalent of cobalt was chosen [11] \(k = 3.4722 \text{[m}^3/\text{A} \cdot \text{s]}\). The part of the electrode and electrolyte that the model includes is about 2 mm wide and the distance between the electrodes is 0.4 mm (0.3 mm if we measure from the peak of the asperity - the value to be used in the calculation). Using equation (1) the maximum expected removal rate of the material can be estimated as [9]:

\[
d(t) = |v| \cdot t = k \cdot |J_n| \cdot t
\]

Knowing that the electrical current density is the ratio of the electrical current to the surface on which it operates and the intensity is the ratio between the electrical potential and the resistance, the latter being considered to be directly proportional to the distance between the electrodes and inversely proportional to the surface of action and the electrical conductivity, it can be deduced a relationship that can characterize the material removal rate by time (equation 3). The cross section of the conductor is reduced, obtaining:

\[
d(t) = k \cdot \frac{U \cdot \sigma}{l} \cdot t
\]
where \( U \) [V] – electrical potential, \( \sigma \) [S/m] – electrical conductivity of the electrolyte, and \( l \) [m] is the distance between anode and cathode. Using the deduced relation (3), it can be estimated the maximum displacement of the material in the y direction, having the following initial data: electrical potential \( U=10 \) V, electrical conductivity of the electrolyte \( \sigma=10 \) S/m, coefficient of proportionality of cobalt \( k=3,4722 \) m\(^3\)·A\(^{-1}\)·s\(^{-1}\). For a polishing regime of 5 seconds under these conditions, it can be obtained the maximum removal of the material in the y direction: \( d (t=5 \) s\)\) = \(5.787\times10^{-5} \) m or \(0.05787 \) mm.

![Figure 3](image-url)  
**Figure 3.** The y-displacement values and the current density after 5 seconds of polishing

![Figure 4](image-url)  
**Figure 4.** Comparison of the analytical and numerical results of the removal rate of materials

In order to compare the obtained analytical result, a model was developed using a multiphysical analysis software [9, 10]. The geometric model is reduced in scale to see more precisely the phenomena that occur during electrochemical polishing. This model uses the "Electric currents" and "Deformed geometry" interfaces of the program. The dynamics of this study is a quasi-static type, and the time dependency only comes in the electrode extenuation (removal of material) [9, 10]. Modeling begins with the definition of constant parameters (in our case the electrochemical equivalent \( k \)) and the realization of the geometry of the model. The electrodes and electrolyte are 2 mm wide and 0.4 mm distance between the cathode and anode. The asperity tip of the anode penetrates the electrolyte by 0.1 mm, so the actual distance between the electrodes is 0.3 mm. The next step is setting the "Electric
currents” module and choosing the stationary form of the equations. This setting specifies that the electrical current distribution can be considered stationary on the time scale determined by the removal rate of the material. As input data it has been considered: electrolyte conductivity $\sigma = 10 \text{ S/m}$ and voltage value $U=10\text{V}$. The upper limit of the cathode is assumed to be $U=0\text{V}$. The final steps for the realization of the model are meshing and defining polishing time. After 5 seconds of polishing at the preset parameters, the numerical value of the material removal or displacement rate for $y$ is $0.06042 \text{ mm}$ (figure 3), a close value to the analytical calculation with relative error of $4.4\%$.

To determine the optimal polishing parameters, the electrical potential - current density curve must be achieved. The reference will be the tip of the asperity, and the other parameters are constant, varying only the voltage. From the figure 5 it results that the suitable voltage in this case is between 11 and 12 V, here is the optimal polishing. Below these voltage values anodic corrosion occurs, and over 12 volts start the gas discharge process, in which case the polishing becomes inefficient, moreover - the material will be attacked.

![Figure 5. Resulted electrical potential - current density curve](image)

Figure 5. Resulted electrical potential - current density curve

Figure 6 shows three-dimensional graphs of displacement and current density according to the main electropolishing parameters. It is to be noted that the other process parameters remain with the same values as in the initial data, varying only the parameters in the graphs.

![Figure 6. Variation of displacement and current density according to time and voltage](image)

Figure 6. Variation of displacement and current density according to time and voltage
Figure 6 demonstrates the formation of gaseous substances and attacking the material at polishing of 60 s and the voltage of 13 V, the displacement increasing sharply, and the current density at the tip of the asperity increases with the growth of the voltage and decreases with time until 13 V, after which the values increase in a chaotic way again, polishing in this case becoming aggressive.

4. Conclusions
Additive manufacturing is becoming increasingly important on the global market due to its exclusive properties, but the big problem remains the quality of printed surfaces, so post-processing steps are indispensable to get reliable finished parts with desirable and high-performance features. In terms of dental bioprosthesis, finishing becomes crucial in order to achieve a prosthetic restoration that will not affect the patient and a long life span. The microscopic investigation has demonstrated the need for additional post-processing, even after manual finishing. One of the most suitable finishing methods of these prostheses is proved to be electrochemical polishing, after which glossy parts with improved fatigue strength are obtained due to the elimination of residual stresses. Corrosion resistance also increases after anodic polishing. Following the theoretical research and the process parameters governing this electrochemical technique, an analytical mathematical model describing the rate of removal of the material has been developed. The analytical model was validated by bidimensional numerical simulation of the process through multiphysical analysis software, obtaining very close results between the analytical and numerical models. The numerical simulation explains in detail the electrochemical principle of removal of the material. Dimensions were used on a miniaturized scale to remark in a more appropriate way the evolution of the main characteristics during the anodic polishing process. The evolution of the main variables was analyzed according to the polishing regime parameters. After this analysis, it is possible to choose the proper polishing regime, the appropriate cathode and the nature of the electrolyte in order to obtain pre-established dental prostheses in subsequent experimental researches.

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