Surface Finishing on the Pivot Orifice of an Artificial Heart Valve Ring

Hengquan Liu, Nan Huang, Yongxiang Leng & Yong Zhang*
Key Laboratory of Advanced Technology of Materials
Chinese Education Ministry
School of Material Science & Engineering
Southwest Jiaotong University
Chengdu, China

The chemical polishing of artificial heart valve rings and the factors influencing surface quality were investigated in this work. The optimum parameters for polishing flat specimens were determined from a fractional factorial design and a few single-factor experiments. The results indicated that a good bright surface was obtained on the valve ring through chemical polishing in the optimum solution, and the pivot orifice surface roughness (R_a) of approximately 0.2 µm could be achieved. This result also provides a simple method to obtain a smooth surface on biomedical titanium.

Keywords: *titanium alloys, chemical polishing, surface quality*

Introduction

Heart valve diseases have a significantly high mortality, and valve replacement using mechanical heart valves (MHVs) is one of the main curing techniques.[1] To date, over two million patients in the world have received artificial heart valve implantations.[2] A prosthetic heart valve is comprised of three primary parts, including the valve ring, the valve leaf and the sewing ring as shown in Fig 1. The valve ring is CNC-machined from a solid block of biomedical-grade titanium, and then painstakingly polished to a mirror surface to reduce the risk of thrombus formation and ensure minimum wear or contact stresses. Manual polishing of the valve ring requires about 8 to 12 hours, an inefficient way of providing a mirror finish. A good bright surface finish was produced by electrochemical polishing in about 45 seconds. However, the manufacturing equipment required to meet the uniformity requirements of the specified finish would be complex and expensive.[3]

Chemical polishing, also known as ion diffusion polishing, occurs when the passive film possesses a physical structure that permits passage of anions to the anode surface by diffusion only.[4] The passive film tends to be thick over micro-recesses but thin over micro-asperities, with corresponding reductions and increases in diffusion rates. The effect is to produce a smooth and polished metal surface.[5] The aim of the present work is to exploit the advantages of enhancing surface quality and reducing the polishing time by this technique.

Experimental

The flat specimens used in this study were biomedical titanium (Grade 2, ASTM 348-83), the same material used in the clinical valve ring. The artificial heart valve ring was formed by CNC-machining, annealed at 550°C under 1.0×10^{-3} Pa. The surface area was calculated after cleaning with acetone.

Three factors, including chemical solution composition, polishing time and polishing temperature, were investigated. The fractional factorial experiment for the polishing solution was based on a four-level design. The experimental design levels are shown in Table l. Each tabulated result was evaluated by taking the average over several readings. The index of surface quality included roughness, reflectivity and average corrosion thickness (*i.e.*, the measure of metal removed during the process). Surface roughness was measured by surface profilometry (AMBIOS XP-2), surface reflectivity was evaluated by an albedometer (C84-II) and the surface morphology of the sample before and after polishing was examined by optical microscopy.

* *Corresponding author:*
Dr. Hengquan Liu
Key Lab of Advanced Technology of Materials
Chinese Education Ministry,
School of Materials Science & Engineering
Southwest Jiaotong University
Chengdu 610031, China
E-mail: 99xyxy@163.com

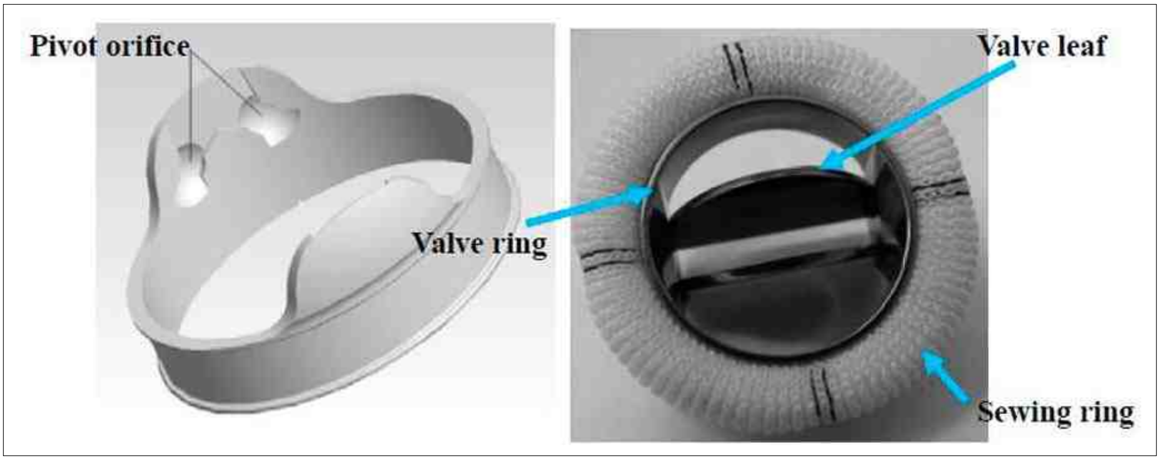

Figure 1 - The pivot orifice of a mechanical heart valve.

Table 1
The experimental design levels of the polishing solution

Factors	1	2	3	4
HNO_3 (65 - 80 wt%)	5 mL	8 mL	1 mL	14 mL
NH_4HF_2 (16 wt%)	2 mL	3 mL	5 mL	7 mL
$HCONH_2$ (16 wt%)	1 mL	2 mL	3 mL	4 mL
H_2O_2 (40 wt%)	5 mL	8 mL	11 mL	14 mL

Results and discussion

Optimum chemical solution

The effective solution composition was determined by polishing titanium plates in accordance with the designed experiment. Sharp spikes were noted in the trace of Fig. 2(a), and the average roughness (R_a) was 1.06 μm. This R_a value was about five times that of the 0.22 μm measured after polishing [Fig. 2(b)]. It was shown that satisfactory results were obtained by chemical polishing in 3.0 min of process time.

The results from the factorial experiment indicate that the concentration of each solution component significantly affects surface quality. There is a concentration of ammonium bifluoride (NH_4HF_2) where the surface roughness is at a minimum (R_a = 0.22 μm), as shown in Fig 3(a). The corrosion thickness or penetration increases linearly as the volume of NH_4HF_2 is increased. Assuming that the fluoride ions from the ammonium bifluoride combine with the hydrogen ions from the nitric acid to form hydrofluoric acid, the corrosivity of the polishing solution was reduced,[6] and the corrosion thickness and nitrogen oxide(s) were diminished accordingly. But the reaction

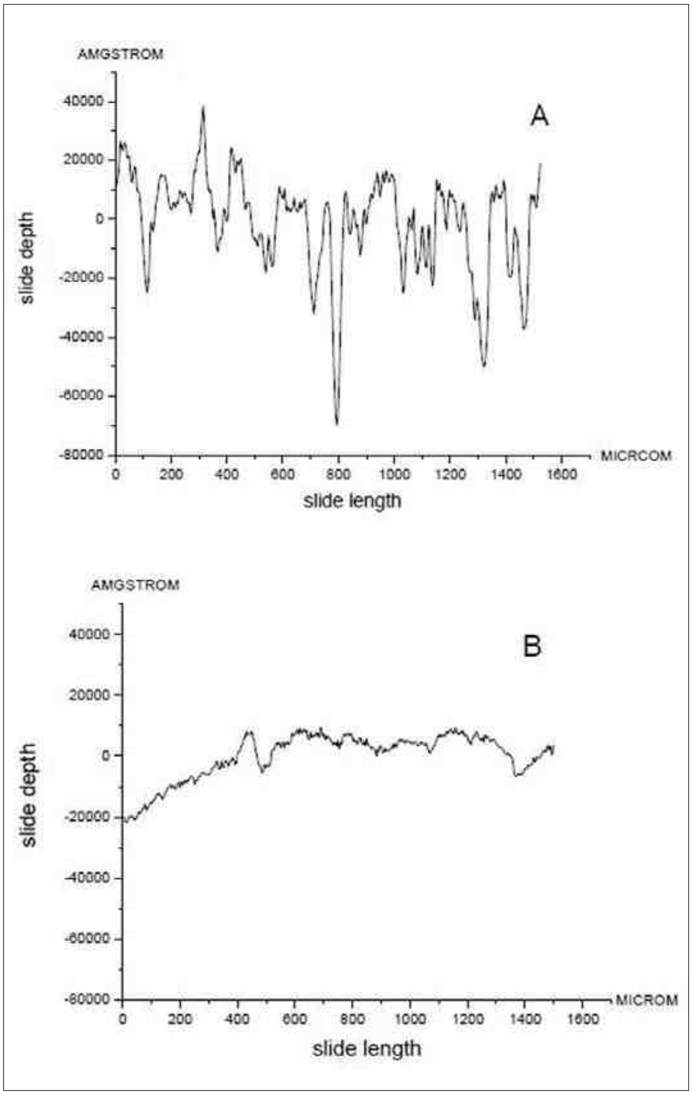

Figure 2 - The roughness curve of the specimen plates: (a) before polishing, (b) after polishing.

rate was reduced as the NH_4HF_2 decreased, and the surface quality was inferior because of insufficient dissolution of the passivation film.[7]

The R_a obtained is strongly related to the nitric acid content, as noted in Fig. 3(b). The optimum concentration of nitric acid was about 11 mL. Excessive corrosion was observed if the volume of nitric acid was above this level. Further, nitrogen oxide(s) were released. However, the surface could not be completely polished owing to the low acidity of the solution.

A suitable surface could be obtained with 12 mL of hydrogen peroxide as shown in Fig. 3(c). In fact, at the lower concentrations, polishing of the titanium alloy was corrupted.[8] Hydrogen peroxide was another oxidizer in this test which weakened the acid strength. Despite the results of our tests, it has been reported that hydrogen peroxide might result in irregular corrosion on the surface.[9]

The surface quality fluctuated with increasing $C_6H_{12}N_4$ concentration as shown in Fig. 3(d). It is very advantageous to maintain the balance at a fixed level in chemical polishing. The $C_6H_{12}N_4$ is used to control the reaction rate in the polishing process. It has also been reported that nitrogen oxide(s) can be incompletely absorbed when the $C_6H_{12}N_4$ content is small.[10] Therefore, it might restrain the release of nitrogen oxide(s). On the other hand, some corrosion products could be observed on the surface if the concentration of $C_6H_{12}N_4$ was too high, and the reaction velocity was gradually limited when metal surface was covered with this residue. The corrosion thickness and reflectivity were influenced as well.

Optimum polishing conditions

Figure 4(a) shows that the R_a has a strong correlation with polishing time. The optimum R_a would be obtained on the "flat" of the curve, at about 2.5 min. Beyond this range, excessive pitting can take place. Nevertheless, if the polishing time is too short, the surface may not be

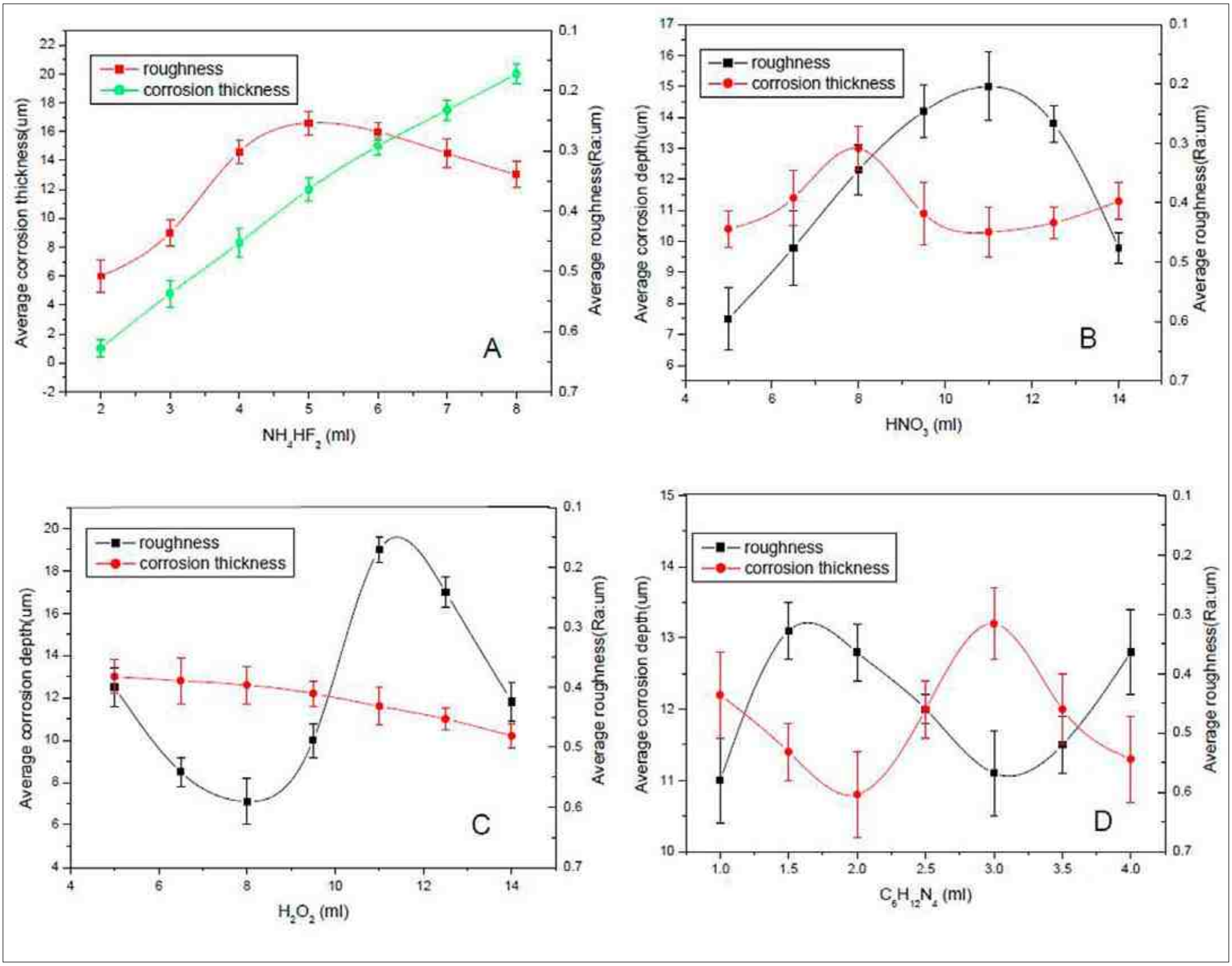

Figure 3 - The solution factors influencing the surface quality of the titanium alloy: (a) ammonium bifluoride, (b) nitric acid, (c) hydrogen peroxide and (d) $C_6H_{12}N_4$.

completely polished. The operating temperature was another factor influencing the average corrosion thickness and the reflectivity. Fig 4(b) shows that the rate of titanium dissolution gradually increased with increasing solution temperature. Nonetheless, polishing can continue to a small extent under 10°C because of the difficulty of dissolving the viscous film which forms at such temperatures. It indicates that the temperature strongly influences the reaction rate and ion diffusion, and consequently influences surface quality.

Optimum additive

The use of additives, such as glycerin, pyridine and vinegar, can aid in enhancing the mirror surface.[11] For example, the glycerin can promote the formation of a passive film, because of its high viscosity. Vinegar can reduce the formation of adherent hydrogen bubbles on the surface, because of reduced surface tension. Thus, any hydrogen embrittlement tendency is accordingly reduced. Pyridine can enhance reflectivity through cleaning of the contaminants adhering to the surface. On the other hand, certain additives can lead to micro-pitting and stress-raisers, which can lower fatigue resistance by as much as 5%.[12]

Figure 5 shows optical microscope images of the pivot orifice of the artificial heart valve ring before and after chemical polishing. The bright finish on the pivot orifice is evident in Fig. 5(b). In the process of polishing the heart valve ring, surface irregularities can be sub-divided into two categories: macroscopic irregularities greater than one micron in size and microscopic irregularities of sub-micron size. The process provided a smoothing action to remove macroscopic irregularities and produce a mirror surface. Thus, chemical polishing is shown to provide a suitable surface on biomedical titanium orifice rings.

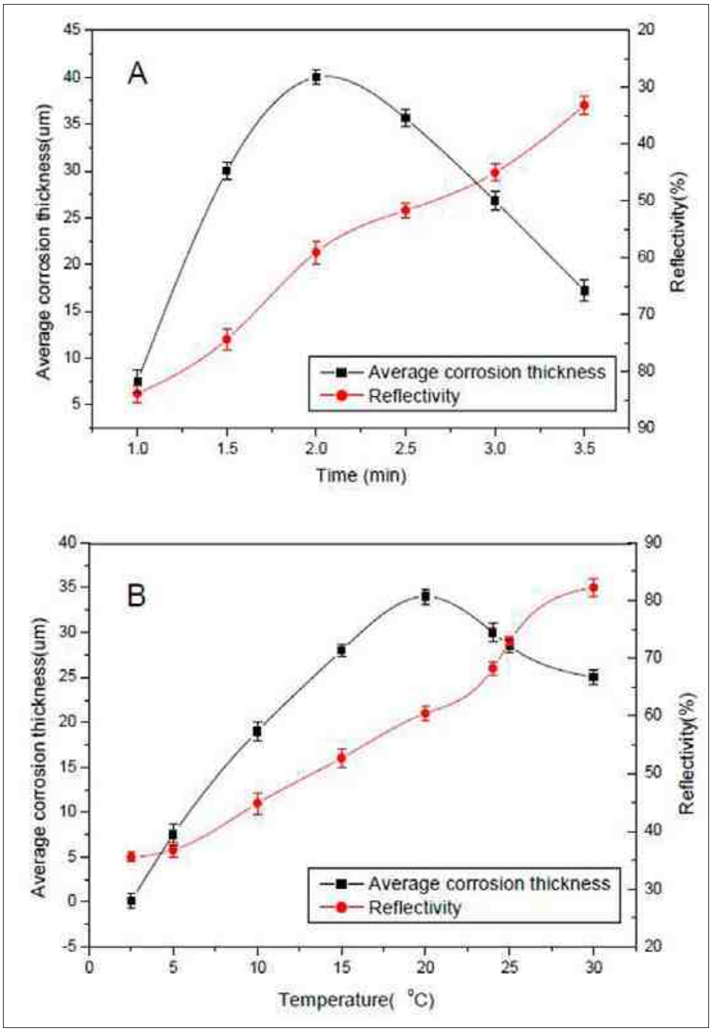

Figure 4 - The influence of (a) temperature and (b) time on the surface quality of the titanium alloy.

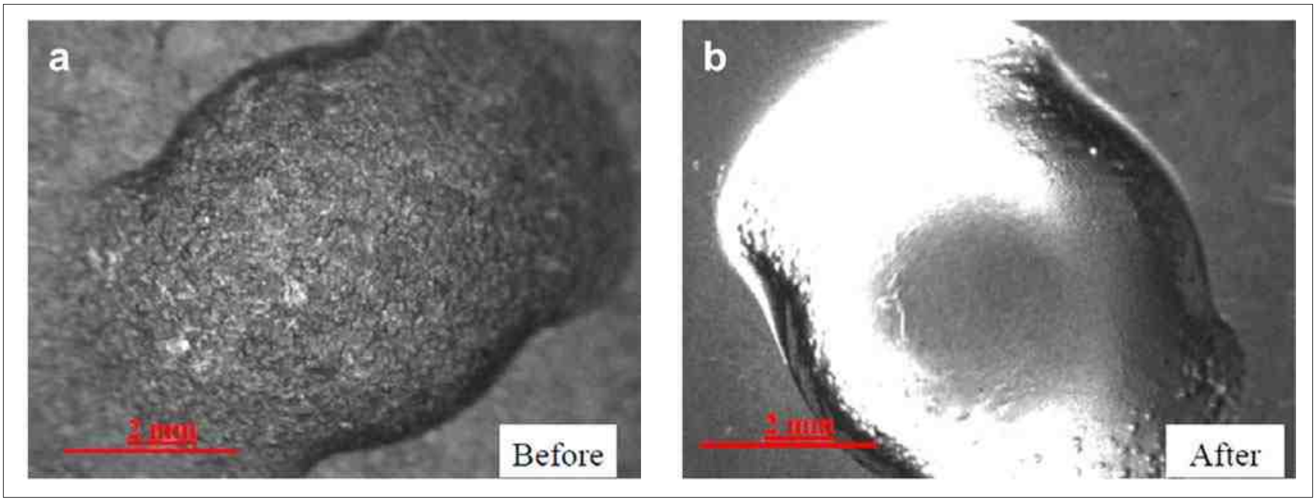

Figure 5 - The pivot surface of a titanium orifice ring (a) before and (b) after polishing.

Conclusions

A bright surface was obtained by chemical polishing of orifice rings with minimal emission of nitrogen oxide(s). Using a fractional factorial experimental design, the factors influencing surface quality were found to include the concentration of solution components, temperature, polishing time and the use of additives. Chemical polishing is an effective way to polish artificial heart valve rings. The technique is also suitable for polishing other biomedical titanium alloy articles of complex shape.

Acknowledgment

This work was jointly and financially supported by Key Basic Research Project No. 2005CB623904, NSFC and the Program for New Century Excellent Talents in University (06-0800)

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About the authors

Hengquan Liu *is a Reading Doctor at Southwest Jiaotong University, Chengdu, China. Dr. Liu has engaged to surface treatment of biomaterials, focusing primarily chemical finishing, electrochemical polishing and surface modification. He has participated numerous projects such as the Key Basic Research Project and the Program for New Century Excellent Talents in University. He is the member of the Chinese Committee for Biomaterials (CCBM).*

Nan Huang *is the Department Head of the School of Material Science & Engineering at Southwest Jiaotong University. Prof. Huang is the Fellow of the Union of International Biomaterials Science & Engineering. He has been the Chairman of the 7th International Workshop of Plasmas Implanting of Biomaterials and the 1st International Conference of Surface and Inter-surface of Biomaterial. Prof. Huang has authored numerous papers on surface treatment and surface modification of biomaterials, including mineral film and biolization coatings. He is active in the International Association of Biomaterials and is currently member of the National Natural Science Foundation of China (NSFC).*