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Surface Performance and Optimization of Nickel Titanium Alloy Electropolishing Parameters

Yongqi Wang, Xiuting Wei[*]*, Zhiyong Li, Xuemin Jing, Zhikang Gong, Chuan Liu*

Shandong University of Technology, School of Mechanical Engineering, 266 xincun west road, 255049, Zibo, China
[*]E-mail: wxt@sdut.edu.cn

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Nickel titanium alloys are widely used in different fields, such as biomedicine, machinery and electronics, and aerospace, because of their shape memory effect, superelasticity, and corrosion resistance. Surface treatment on nickel titanium alloy is necessary to reduce metal ion released in human tissues and prevent human poisoning and organ failure. This paper proposes an electropolishing method for optimizing the surface quality of nickel titanium alloy pipes. A hybrid electropolishing solution suitable for nickel titanium alloy pipes was determined through experiments. The four factors affecting the electropolishing process were analyzed and the best polishing parameters were obtained through orthogonal experiment and single factor experiment. Quantitative statistics revealed that the material removal of the electropolishing method is controllable. Finally, a nickel titanium alloy pipe with low surface roughness (40.7 nm) and good surface morphology was obtained.

Keywords: Electropolishing; Nickel titanium alloy pipe; Surface properties; Ra; Material removal

1. INTRODUCTION

Nickel titanium alloy is an important metal because of its shape memory effect, superelasticity, and corrosion resistance; thus, it is widely used in various fields, such as biomedicine, mechanical electronics, aerospace, and other fields [1-3]. In biomedicine, its performance is better than that of common medical stainless steel and can meet the needs of various medical applications. The prevalence of various heart diseases and cerebrovascular diseases has increased with negative changes in lifestyle [4]. Deaths due to cardiovascular and cerebrovascular diseases account for about one third of all deaths due to diseases at the beginning of 2000s [5]. This number increased to 55.7% in 2020, and four-fifths of these deaths occurred in low- and middle-income countries. The proportion is still rising and is expected to exceed 60% in 2021 [6]. Interventional medical equipment made of nickel titanium alloy has been recognized by patients and doctors because it causes less trauma during surgery, it has high safety, and patients have quick recovery after surgery. Therefore, the number of people who use this material in treatment is increasing [7,8]. However, nickel titanium alloy is in direct contact with human tissues in the human body; therefore, the requirements for its surface integrity, roughness, and geometric accuracy are very strict.

The processing methods used for medical nickel titanium alloys include lithography, laser machining, and electrical discharge machining [9-11]. However, the surface morphology and roughness of nickel titanium alloy pipes treated through these methods have not been optimized. Therefore, surface treatment is needed to reduce the metal ions released by the pipe in human tissues and prevent metal poisoning and organ failure [12-14]. Electropolishing can ensure the shape and size of the workpiece and improve surface morphology and surface roughness [15,16]. Therefore, electropolishing is an ideal process for the post-treatment of medical nickel titanium alloy pipes.

Researchers have carried out several studies on the electropolishing of nickel titanium alloy. Barison et al. studied the electropolishing of nickel titanium alloy in methanol–sulfuric acid electrolyte and found that heat treatment in air at 450 °C leads to the formation of a thick oxide layer with a thickness of about 80 nm [17]. Lee et al. studied the electropolishing of nickel titanium alloy using an electrolyte composed of phosphoric acid, sulfuric acid, and water; analyzed the surface state after electropolishing; and obtained the processing conditions suitable for electropolishing nickel titanium alloy [18]. Ha et al. used a combination of electrolytic polishing and mechanical polishing to improve the surface integrity of nickel titanium alloys. Surface roughness can be greatly improved by polishing [19]. Lugovskoy et al. electropolished nickel titanium alloy wire using sulfuric acid, methanol, and glycerin as electrolytes and studied the corrosion mechanism of nickel titanium alloy wire in two solutions. They found that the activity of nickel titanium alloy wire in Hanks solution is lower than that in sodium chloride [20]. Simka et al. evaluated the effect of electropolishing on the surface morphology and roughness of nickel titanium alloys. A uniform nickel titanium alloy surface can be obtained using a polishing solution with hydrofluoric acid and sulfuric acid as electrolytes [21]. Neelakantan et al. used a rotating disk electrode to study the electropolishing of nickel titanium alloy and analyzed the influence of rotation speed, temperature, and the addition of Ni and Ti ions on the dissolution kinetics [22]. Wever et al. studied the corrosion resistance and surface characteristics of nickel titanium alloy surface. Another study found that a TiO_2-based oxide layer forms on the surface of nickel titanium alloy after electropolishing and reduces the nickel content in the outermost surface layer [23].

Current research use nickel titanium alloy plate as the electropolishing object. Nickel titanium alloy pipe is quite different from a flat plate; therefore, the electropolishing process for the flat plate is obviously not suitable for the pipe. This study aimed to investigate the influence of different electropolishing factors on the pipe and improve the surface performance of the pipe while ensuring that the polishing process is controllable and efficient. In this study, the electropolishing solution based on glacial acetic acid–perchloric acid was optimized using two solvents, the influence degree of electropolishing factors was analyzed, and the electropolishing parameters were optimized; and the surface morphology, roughness, and material removal rate before and after electropolishing were characterized.

2. EXPERIMENTAL

The nickel titanium alloy pipe (52.3 at.% Ni) used as the workpiece was produced by Jiugang Group. The outer diameter of the pipe is 2.65 mm, and the wall thickness is 0.24 mm. We used an automatic pipe fiber laser cutting machine (LF90M model) to cut the pipe into 13 mm sections. The cut nickel titanium alloy pipe was ultrasonically cleaned in ethanol for 90 s and blow dried. The laser-cut pipe will inevitably have impurities, such as slag and oxide scale; therefore, mechanical polishing is necessary before electropolishing. First, the pipes were sanded using 400#–2000# sandpapers to remove most of the surface oxide scale and slag, and then ethanol and acetone were used for 180 s to ultrasonically clean the pipes. Afterwards, the pipes were dried and placed in a drying box. The surface roughness and surface morphology of the pipes were obtained using an optical profiler (MicroXAM-100) and a field-emission environmental scanning electron microscope. This paper chose the arithmetic mean roughness (Ra) as the evaluation parameter because it can provide the most information on surface roughness.

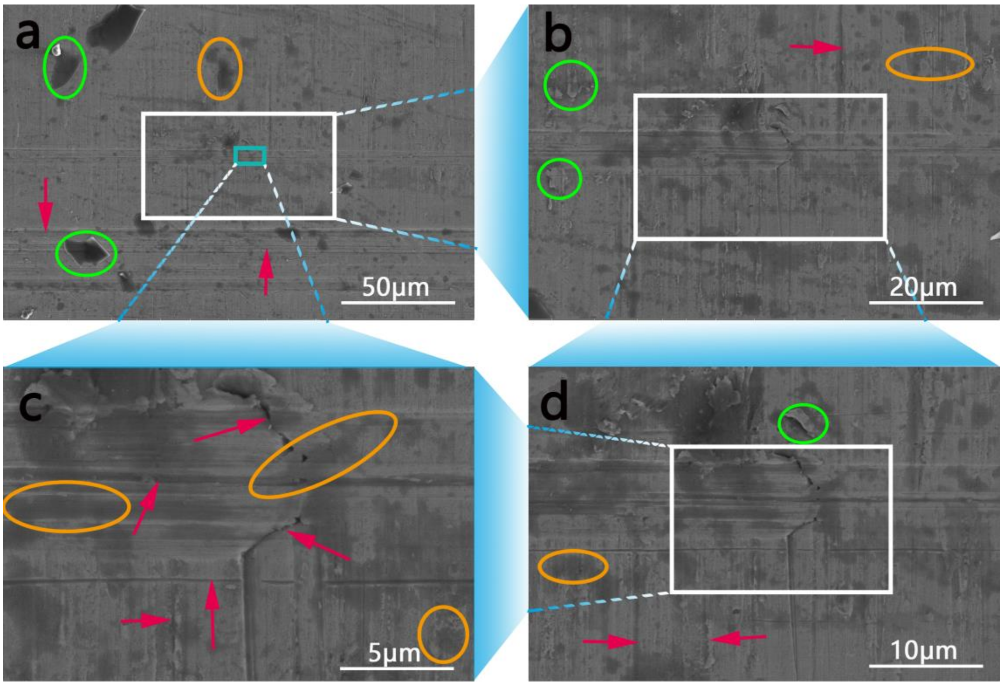

Figure 1. Surface microstructure of nickel titanium alloy pipe: (a) 2000×, (b) 5000×, (c) 10000×, (d) 20000×

Three different positions were selected for measurement, and the measurement was repeated three times for each position and averaged. The result shows that the Ra of the nickel titanium alloy pipe is 1.37 μm. Figure 1 shows the microtopography of the pipe surface after laser cutting. The figure shows the presence of slag (marked in green), black oxide (marked in orange), and scratches (marked in red) on the surface of the tube. Figures 1b–1d are the partial enlarged views of Figure 1a. The flatness of the tube surface is relatively poor; thus, its surface morphology needs to be improved.

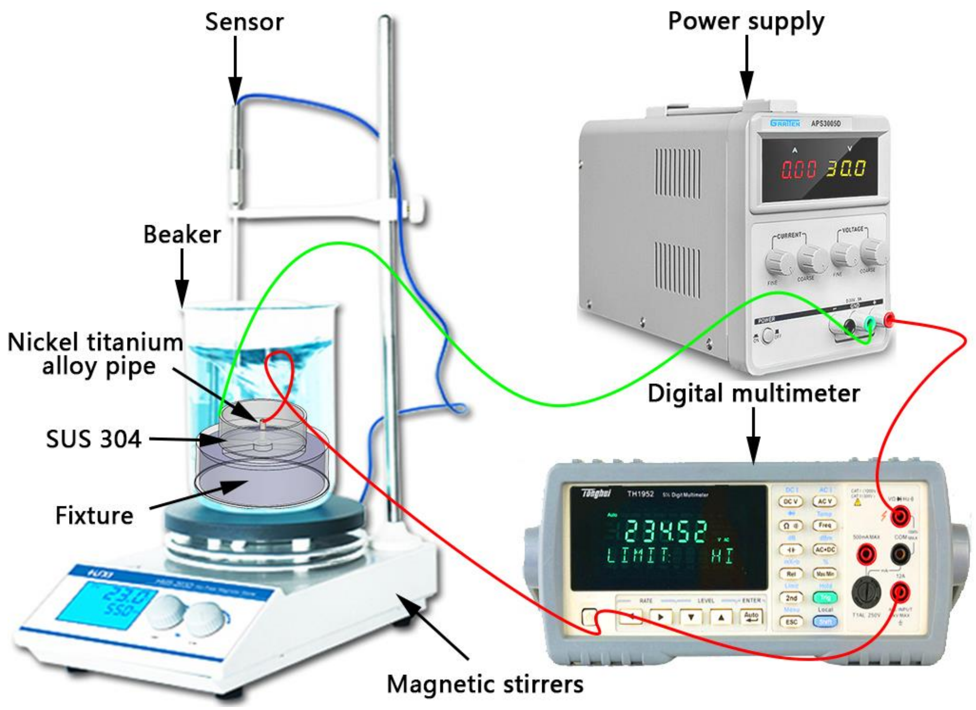

Figure 2. Schematic diagram of electropolishing device for nickel titanium alloy pipes

Table 1. Electropolishing parameters

Electrolyte			Voltage（V）	Temperature（℃）	Distance between cathode and anode（mm）	Time（s）
Basic electrolyte	Additive（g/L）	Corrosion inhibitor（ml/L）				
Acetic acid-perchloric acid 11:1-21:1	Glucose 1-9	Methanol 10-130	4-32	8-30	10-30	50-150

Figure 2 is the schematic diagram of a platform for electropolishing experiments. The electrolyte was placed in the beaker, and the temperature was detected and controlled by a magnetic stirrer. The electrolyte was stirred with a stirring bar at 300 rpm to speed up circulation. The anode is the electrolytically polished nickel titanium alloy pipe, and the cathode is a stainless-steel ring. The range of electropolishing parameters is shown in Table 1. The polished stent sample has a certain polishing effect under this process condition.

3. RESULTS AND DISCUSSION

3.1 Optimization of electrolyte

3.1.1 Optimization of basic electropolishing liquid

Based on the literature and the results of the preliminary experiment, the electropolishing process conditions for the optimization of the electropolishing solution were as follows: the volume ratio of acetic acid to perchloric acid was 11:1–21:1, voltage was 14 V, polishing temperature was 20 °C, the distance between cathode and anode was 20 mm, and polishing time was 100 s. Ra and surface morphology were used as indicators to determine the result of electropolishing. Figure 3 shows the Ra of the electrolyte with different volume ratios after polishing. The figure shows that surface roughness initially decreased and then increased.

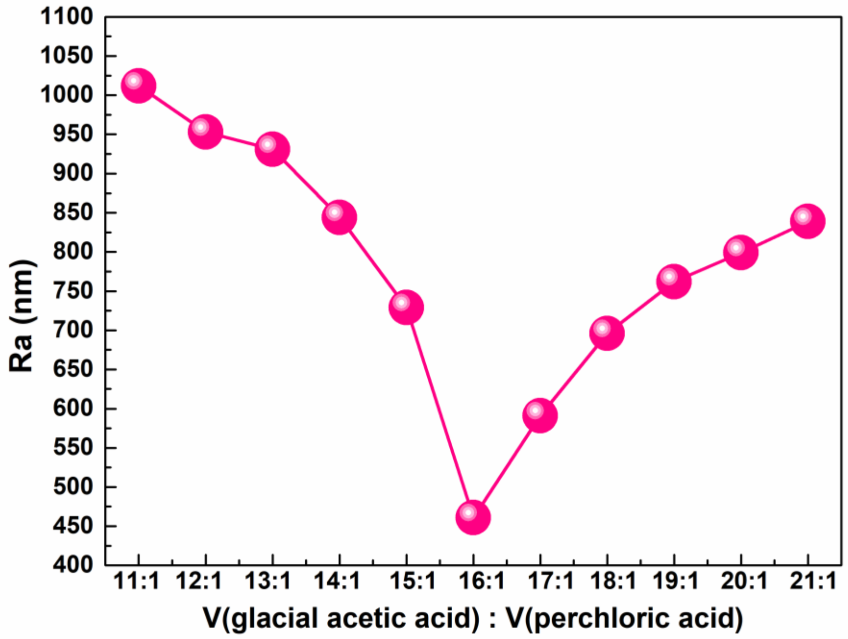

Figure 3. Changes in surface roughness based on the volume ratio (11:1–21:1) of acetic acid to perchloric acid

The surface roughness was 1012.0 nm when the volume ratio of acetic acid to perchloric acid was 11:1. The surface roughness of the pipe gradually decreased as the content of acetic acid increased. The minimum roughness value of 461.1 nm, a decrease of 54.45%, was obtained when the volume ratio was 16:1. However, the surface roughness of the pipe began to gradually increase when the acetic acid content was further increased. When the volume ratio was 21:1, the surface roughness reached 839.2 nm, which is increased by 82.00% compared with the minimum roughness of 461.1 nm. The surface morphology of the nickel titanium alloy pipes with different volume ratios of acetic acid to perchloric acid is shown in Figure 4.

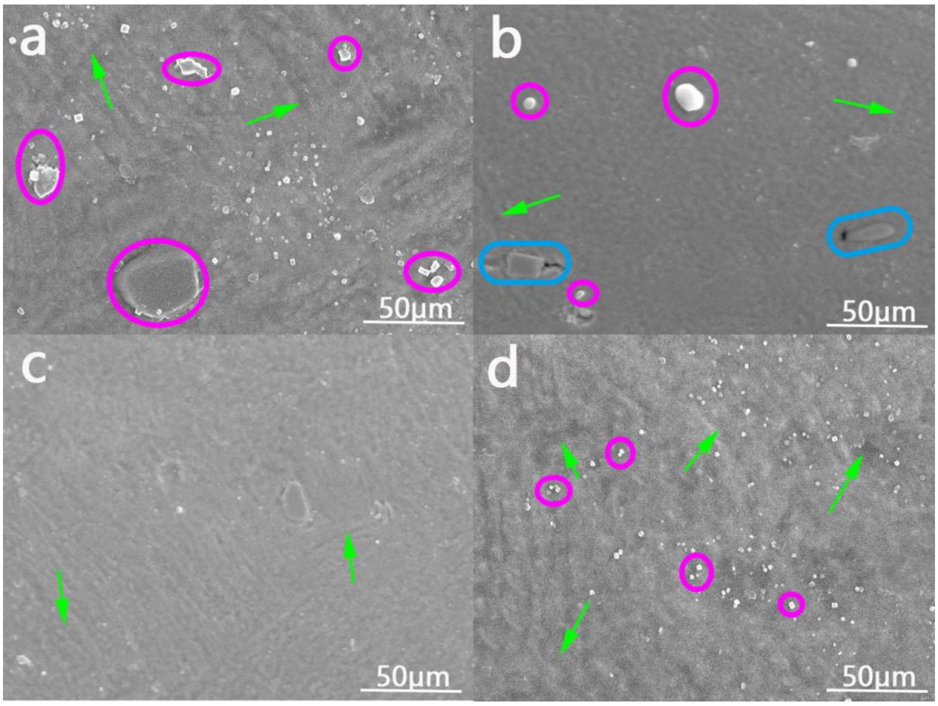

Figure 4. Micromorphology of the pipe with different acetic acid–perchloric acid ratios after electropolishing: (a) 11:1, (b) 14:1, (c) 16:1, (d) 21:1

The figure shows that the change in surface topography is consistent with the change in roughness. The roughness was the lowest, the surface morphology was relatively flat, and the morphology was better than those in other content ratios when the volume ratio was 16:1 (Figure 4c). The content of perchloric acid in the solution increases when the volume ratio is lower than 16:1. Perchloric acid is more oxidizing; therefore, the corrosion ability of the electrolyte on the pipe was enhanced at this ratio [24]. The pipe surface became prone to pitting corrosion, which results in obvious pits or bumps, and the polishing uniformity became poor when the pipe was exposed to high perchloric acid content (Figures 4a and b). When the volume ratio was higher than 16:1, the oxidizing property of the electrolyte relatively weakened. Therefore, the polishing ability of the electrolyte on the pipe deteriorated, and the improvement of defects, such as bumps and scratches, on the surface of the material itself was not obvious as shown in Figure 4d.

3.1.2 Effect of corrosion inhibitor

Acetic acid is prone to solidification because its melting point is relatively low (16.6 °C) [25]. Therefore, this article explored the effect of adding methanol to the basic electropolishing solution with the best volume ratio on the pipe surface. Methanol has a low melting point (−97.8 ℃), which can effectively prevent the solidification tendency of basic electrolyte and facilitate the polishing process [26]. In addition, the hydroxyl in methanol can delay corrosion and adjust the pH value of the solution to improve the polishing effect. However, too high or too low methanol concentration adversely affects the surface morphology of the tube. When the concentration was too low, the effect on improving the freezing point of the basic electropolishing solution was limited, and the viscosity of the solution was very high at low temperature. When the concentration was too high, the base electropolishing solution was too diluted and the viscosity was too low. At this time, the nickel titanium alloy pipe underwent oxygen evolution reaction, which produced stripes on the surface and subsequently increased surface roughness and led to poor polishing effect. The test was conducted in nine groups, and each group contained three test pieces. After the test, the nickel titanium alloy pipe was ultrasonically cleaned and dried, and the surface roughness of the tube was measured with an optical profiler. The test parameters and results are shown in Figure 5.

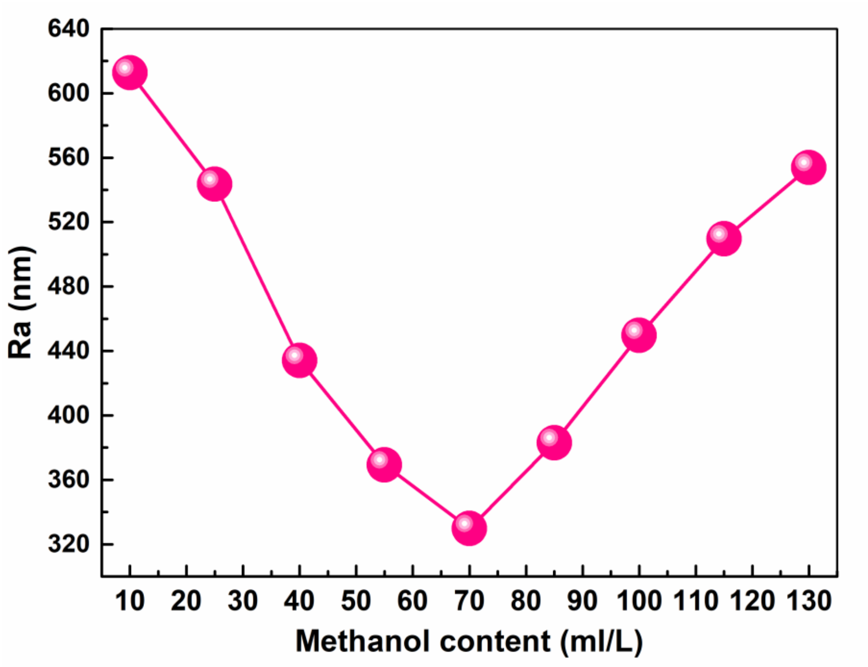

Figure 5. Influence of methanol content (10–130 mL/L) on pipe roughness

As shown in Figure 5, the surface roughness of the tube initially decreased and then increased with the gradual increase in methanol content. When the added content was 10 mL/L, the roughness was 612.7 nm, which was 151.6 nm higher than the roughness of the basic polishing liquid with the best volume ratio; therefore, this content is not conducive for reducing surface roughness. The roughness decreased to the minimum value of 329.8 nm when the methanol content was increased to 70 mL/L. However, the roughness increased again when methanol content further increased. The surface morphology at different methanol concentrations is shown in Figure 6.

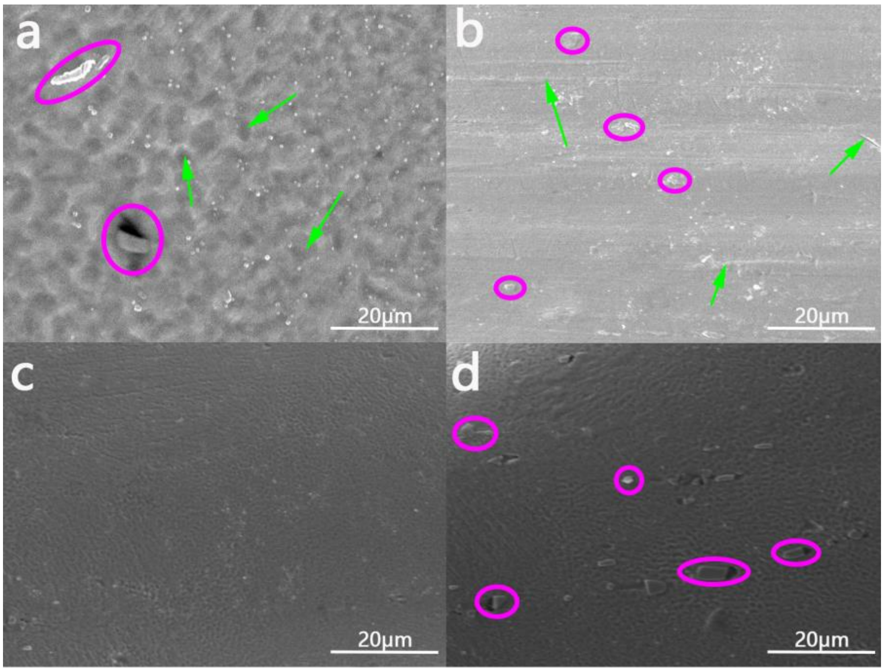

Figure 6. Surface micro morphology of the pipe under different methanol contents: (a) 10 mL/L, (b) 40 mL/L, (c) 70 mL/L, (d) 130 mL/L

Figure 6 shows that when the methanol content was low, the surface of the tube had a large number of pits and bumps, the flatness was poor, and the polishing effect was not good (Figures 6a and b). When the methanol content was 70 mL/L, the surface morphology greatly improved, the flatness improved, and the electrolytic polishing effect was relatively good (Figure 6c). As the methanol content continued to increase, the bumps on the surface were not completely polished, and the polishing effect became remarkably worse (Figure 6d). Therefore, the optimal methanol content is 70 mL/L.

3.1.3 Effect of additives

Adding appropriate additives to the electropolishing solution can effectively improve the polishing effect [27]. Therefore, different levels of glucose were added to the basic electropolishing solution with the best ratio to explore the influence of glucose on the electropolishing of nickel titanium alloy pipes. The surface roughness was tested with an optical profiler, and the result is shown in Figure 7.

As shown in Figure 7, the surface roughness of the nickel titanium alloy pipe shows W-shaped fluctuations as the glucose content increased. The surface roughness of the pipe initially decreased and then increased when the glucose content was lower than 3 g/L and continued to decrease and increase as the glucose content continued to increase. On the whole, the surface roughness of the pipe reached the minimum value of 213.7 nm when the content was 6 g/L. The microtopography map (Figure 8) shows that the addition of glucose can improve the microtopography of the pipe.

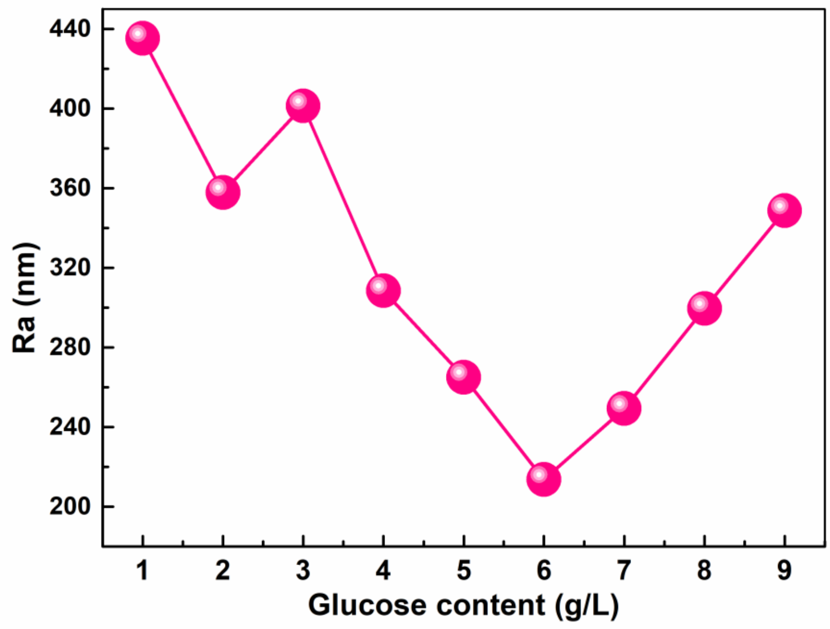

Figure 7. Influence of glucose content (1–9 g/L) on pipe roughness

Low glucose content has a certain leveling effect on the nickel titanium alloy pipe; however, it causes striped defects on the surface, and bumps are not completely removed (Figures 8a and b). When the glucose content reached 6 g/L, the surface morphology of the pipe was relatively good. The convexity and streak defects on the surface disappeared, and the surface flatness was relatively high. As glucose continued to rise, uneven defects began to appear on the surface of the nickel titanium alloy pipe, and the polishing effect became worse (Figure 8d). Therefore, the optimal content of glucose is 6 g/L.

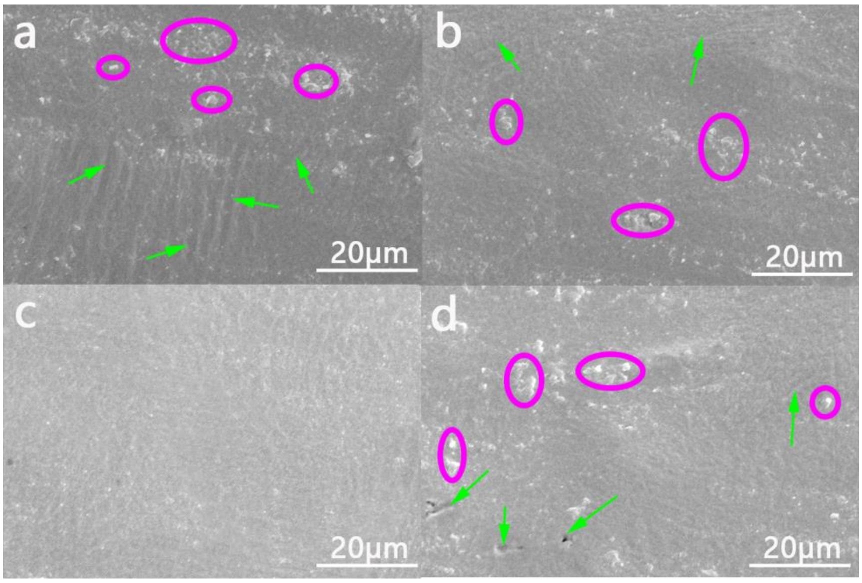

Figure 8. Surface microstructure of the pipe under different glucose contents: (a) 2 g/L, (b) 4 g/L, (c) 6 g/L, (d) 9 g/L

3.2 The influence of electropolishing parameters

The composition of the optimized electropolishing solution includes acetic acid–perchloric acid solution with a volume ratio of 16:1, 70 mL/L methanol, and 6 g/L glucose. The surface condition of the nickel titanium alloy pipe under the preliminarily selected process parameters improved to some extent but still cannot meet the requirements of use [28]. The electropolishing parameters (voltage, polishing time, distance between cathode and anode, and polishing temperature) should be further optimized to improve the polishing effect. This paper designed an orthogonal experiment with four factors and three levels, which can accurately and efficiently explore the influence of different polishing factors. The orthogonal array is shown in Table 2.

Table 2. Orthogonal test factor level table

Factor	Voltage (v)	Temperature (°C)	Time (s)	Distance between cathode and anode (mm)
Level 1	10	15	80	16
Level 2	14	20	100	20
Level 3	18	25	120	24

Surface roughness was used as the evaluation index, and the test parameters and results are shown in Table 3. The values in Table 4 were obtained by calculation according to the results in Table 3. Average value 1 (2, 3) in Table 4 represents the average roughness measured under the same level of the factors in this column. The optimal combination of process parameters was selected to minimize the surface roughness of the nickel titanium alloy pipe. The optimal process parameters were as follows: voltage, level 3; temperature, level 2; time, level 3; distance between cathode and anode, level 2. The difference between the maximum and minimum values of surface roughness in each column is expressed as R. The degree of influence of the four parameters on electropolishing can be judged according to the size of R. According to the comparative analysis of R, voltage has the greatest influence on the surface roughness among the four influencing factors, followed by temperature, distance between cathode and anode, and polishing time. Therefore, the optimal process parameters selected by orthogonal experiment are as follows: voltage, 18 V; temperature, 20 °C; distance between cathode and anode, 20 mm; and polishing time, 120s.

Table 3. Orthogonal test parameters and surface roughness

Test	Voltage (v)	Temperature (°C)	Time (s)	Distance between cathode and anode (mm)	Surface roughness Ra (nm)
1	10	15	80	16	219.5
2	14	15	100	20	189.9
3	18	15	120	24	165.9
4	10	20	100	24	174.2
5	14	20	120	16	159.9
6	18	20	80	20	122.7
7	10	25	120	20	179.8
8	14	25	80	24	183.2
9	18	25	100	16	153.7

Table 4. Average and range of roughness in each factor

Factor	Voltage (v)	Temperature (°C)	Time (s)	Distance between cathode and anode (mm)
Average value 1	**191.17**	**191.76**	**175.13**	**177.7**
Average value 2	**177.67**	**152.27**	**172.6**	**164.13**
Average value 3	**147.43**	**172.23**	**168.53**	**174.43**
R	**43.74**	**39.49**	**6.6**	**13.57**

The influence of various electropolishing factors on the surface of the tube was explored to further improve the electropolishing process. Orthogonal experiments and single factor experiments were carried out according to the degree of importance to further optimize the electropolishing parameters.

3.2.1 Effect of voltage

The test shows that voltage has the greatest influence on the surface of nickel titanium alloy pipe. Therefore, the influence law of voltage was first explored. Voltage in the range of 4–32 V was used as the single-factor variable. The remaining parameters were as follows: polishing temperature, 20 °C, the distance between cathode and anode, 20 mm, and polishing time, 120 s. After the test, the measured surface roughness was sorted, and a graph of the influence of voltage on surface roughness was drawn as shown in Figure 9.

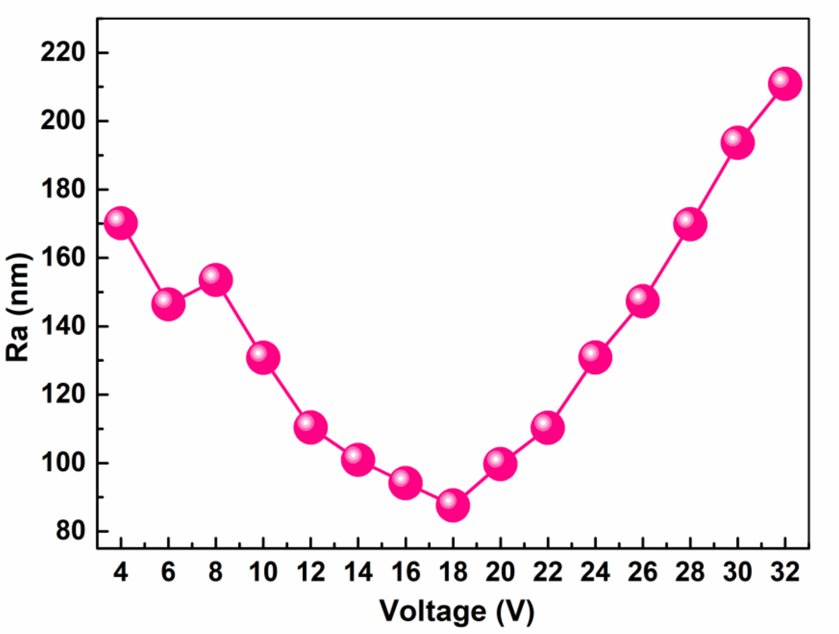

Figure 9. Influence of voltage (4-32 V) on the surface roughness of nickel titanium alloy pipe

Surface roughness initially decreased and then increased as the voltage increased. The surface roughness value was 170.1 nm when the voltage was 4 V. When the voltage was increased to 18 V, the surface roughness value decreased to 87.6 nm. Thus, the surface quality of the pipe improved as the voltage increased. However, the surface roughness showed an upward trend when the voltage was further increased. Surface roughness increased to 210.8 nm when the voltage was 32 V. The result shows that high voltage will have an adverse effect on surface quality. Therefore, the minimum roughness of the pipe (87.6 nm) can be obtained at the voltage of 18 V.

3.2.2 Effect of temperature

Temperature is the second most important factor that affects the surface quality of nickel titanium alloy pipes. Therefore, temperature was used as the test variable, and the other electropolishing parameters were set as follows: optimal voltage, 18 V, distance between cathode and anode, 20 mm, and polishing time, 120 s. The relationship between the surface roughness of the pipe and the temperature of the electropolishing solution is shown in Figure 10. The surface roughness of the nickel titanium alloy pipe initially decreased and then increased as the polishing temperature increased. When the temperature increased from 8 °C to 18 °C, the corresponding surface roughness decreased from 248.9 nm to 84.3 nm. When the temperature was further increased to 30 °C, the surface roughness of the tube gradually increased to 223.7 nm. Therefore, the minimum surface roughness of the nickel titanium alloy pipe (84.3 nm) can be obtained when the temperature of the electropolishing solution is 18 °C.

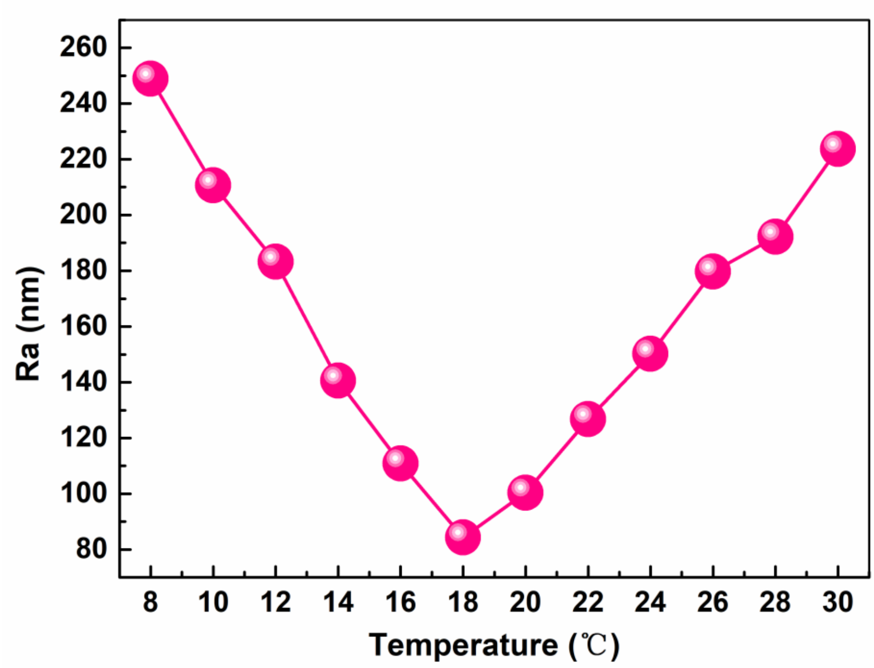

Figure 10. Influence of polishing temperature (8-30 °C) on surface roughness

3.2.3 Effect of distance between cathode and anode

The distance between the anode and cathode was used as the test variable to explore its influence on the surface quality of the nickel titanium alloy pipe. The optimum voltage and electropolishing temperature were used, and the polishing time was 120 s. The influence of distance on the surface roughness of nickel titanium alloy pipe is shown in Figure 11. The surface roughness of the tube decreased initially and then increased as the distance increased. The surface roughness decreased rapidly from 269.1 nm to 85.7 nm at the distance of 10–20 mm. The surface roughness began to increase gradually when the distance exceeded 20 mm. The surface roughness was 172.9 nm when the distance was 30 mm. Therefore, the best distance between cathode and anode is 20 mm.

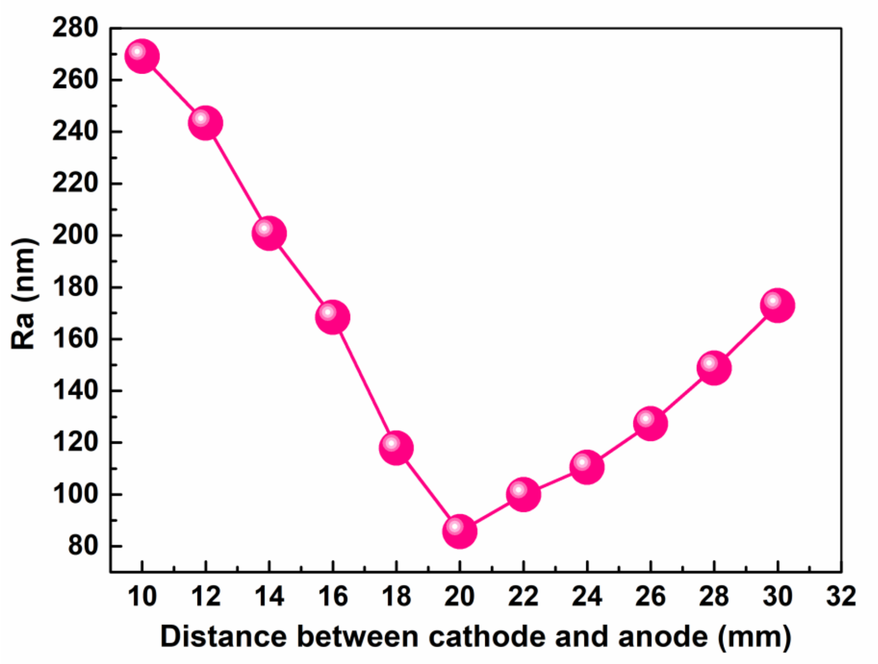

Figure 11. Influence of the distance between cathode and anode (10-30 mm) on surface roughness

3.2.4 Effect of time

The variation in the roughness of nickel titanium alloy pipes in different polishing times was explored. Time was used as the single variable (50–150 s), and the other electropolishing factors were as follows: optimum voltage, 18 V; optimum polishing temperature, 18 °C; and optimum distance between cathode and anode, 20 mm. The influence curve of polishing time on surface roughness is shown in Figure 12. Surface roughness initially decreased and then increased as the polishing time increased. The surface roughness of the pipe gradually decreased with time until the minimum value was 40.7 nm when the polishing time was less than 100 s. The roughness gradually increased when the polishing time exceeded 100 s and reached 132.7 nm at 150 s. Therefore, the best polishing time is 100 s. At this time, the nickel titanium alloy pipe has the best surface roughness of 40.7 nm.

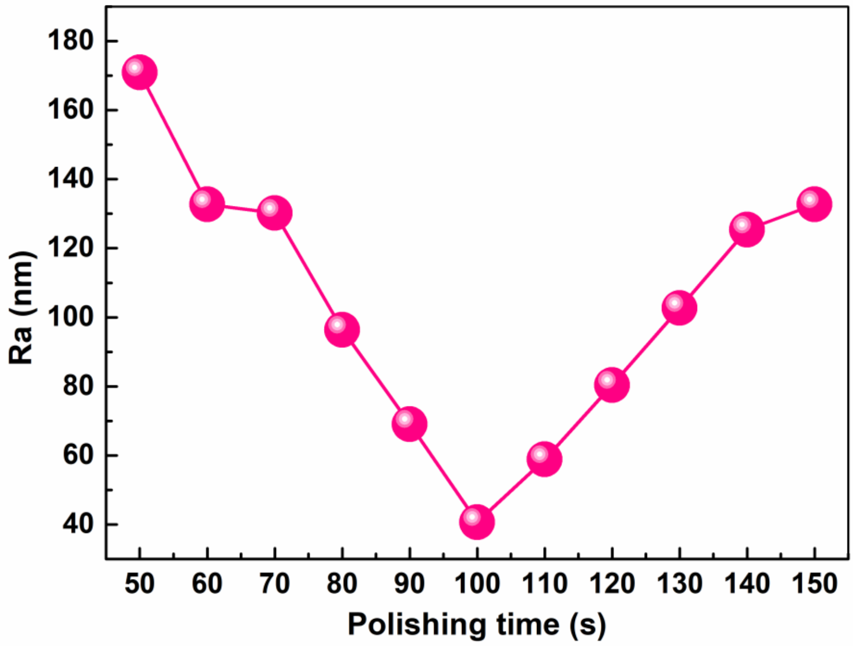

Figure 12. Effect of polishing time (50–150 s) on surface roughness

3.3 Electrolytic polishing rate and surface morphology

As a medical metal material for the human body, the surface condition of the nickel titanium alloy pipe and the dimensional change after electropolishing will have a serious impact on subsequent use. Therefore, the material removal rate in the electropolishing process is necessary to explore. This paper studied the variation in the thickness of the nickel titanium alloy pipe with polishing time when the best polishing parameters and electrolyte solution were used. An optical profiler was selected for non-contact measurement to accurately measure wall thickness. In this way, errors from the deformation caused by contact measurement, such as vernier calipers, can be avoided. Each pipe was measured three times at different positions, and the average value was considered the experimental result. Figure 13 is a graph of the variation in the wall thickness of the pipe with polishing time. The wall thickness of the nickel titanium alloy pipe gradually became smaller and presented a linear state as the polishing time was prolonged. The wall thickness was reduced by 24.9 μm from the original 240 μm to 215.1 μm when polished in optimum polishing time (100 s); thus, the removal rate is 0.249 μm/s. The wall thickness was 204.6 μm, which is 35.4 μm smaller than the original size, when the polishing time was 150 s.

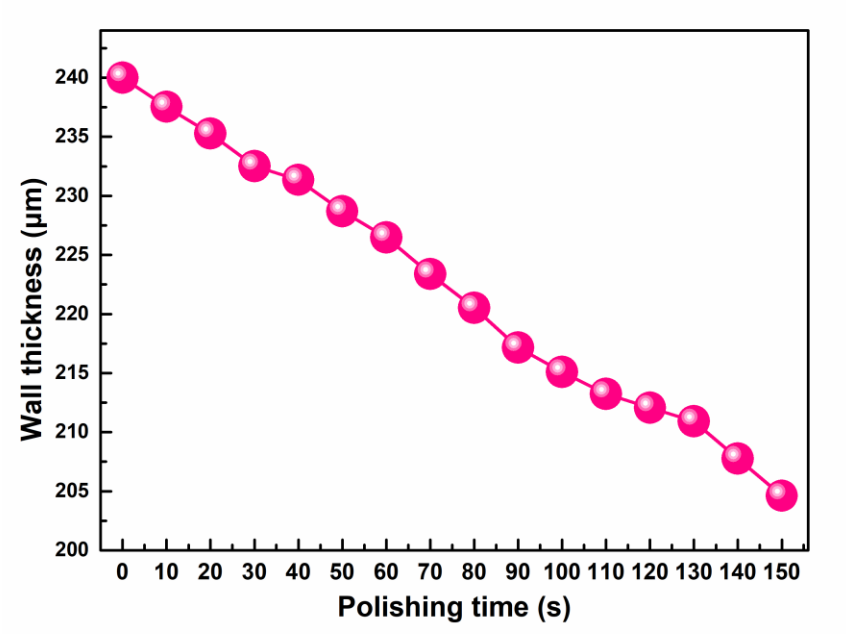

Figure 13. Variations in the wall thickness of nickel titanium alloy pipe with polishing time (0–150 s)

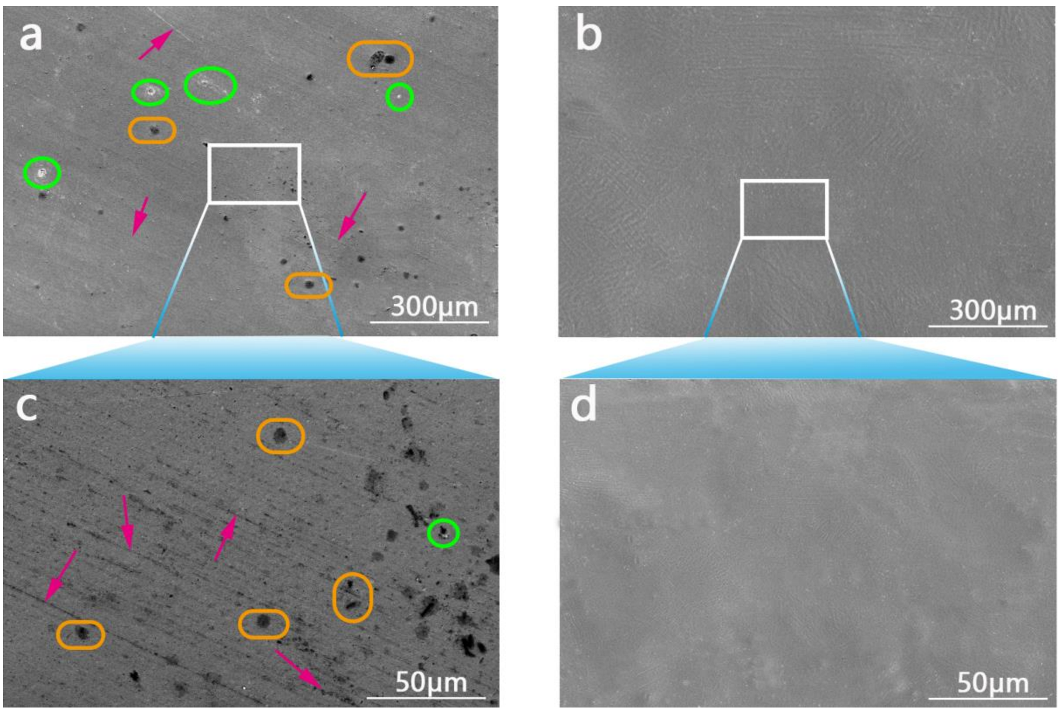

Figure 14. Surface morphology of nickel titanium alloy pipe before and after electropolishing

Figure 14 is a comparison diagram of the surface morphology of nickel titanium alloy pipes before and after electropolishing using the best polishing parameters. Figures 14a and c are the low and high magnification images of the pipes before polishing. The figures show that the surface of the tube is uneven and still has some scratches, and the surface flatness is very poor. Figures 14b and d show that the scratches on the surface of the material disappeared, and the material was smooth and bright after electropolishing. Thus, the surface quality of the nickel titanium alloy pipe was greatly improved by electropolishing.

3.4 Comparison with similar results

Current research have used nickel titanium alloy plate as the electropolishing object [29, 30, 31, 32]. However, these researches did not verify the degree of influence of electropolishing factors, the effect of the addition of corrosion inhibitors and additives, and the material removal rate of electropolishing solutions. These studies obtained relatively lower surface roughness than this article, but the gap is not big. The possible reason for the low surface roughness is that their research objects are flat plates, whereas the research object of this article is a pipe. The electropolished surface of the pipe is curved and is more difficult to polish than a plate. Only one literature explored nickel titanium alloy pipe [33], but it did not study the material removal rate and used a different electrolyte, which produced a higher surface roughness than that obtained in this article (See Table 5 for specific comparison).

Table 5. Compared with similar discussion and results

No.	Research object	Electrolyte	Factor influence (decreasing)	Additive experiment	Ra (nm)	Material removal rate	Ref.
1	Nitinol plate	acetic acid	N.A.	N.A.	Increase 0.43nm	N.A.	[29]
2	Nitinol plate	sulfuric acid and methanol	N.A.	N.A.	39.7	N.A.	[30]
3	Nitinol plate	phosphoric acid, sulfuric acid and distilled water	N.A.	N.A.	41.3	N.A.	[31]
4	Nitinol plate	sulfuric acid and methanol	N.A.	N.A.	Over 20	N.A.	[32]
5	Nitinol pipe	perchloric acid and methanol	exist	triethanolamine and absolute ethanol	48.6	N.A.	[33]
6	Nitinol pipe	acetic acid and perchloric acid	voltage, polishing time, distance between cathode and anode, and polishing temperature	methanol and glucose	40.7	0.249μm/s	This work

4. CONCLUSIONS

This article takes nickel titanium alloy pipe as the research object and proposes a polishing solution suitable for electropolishing nickel titanium alloy pipe. The influencing factors of the electropolishing process were studied through experiments, and the degree and law of influence of each factor on the polishing effect were determined. Then, the parameters of each factor were optimized through single factor experiments. The best electropolishing parameters were used to greatly improve the surface quality of the nickel titanium alloy pipe. The main conclusions are as follows:

(1) The best volume ratio of acetic acid to perchloric acid in the basic electropolishing solution is 16:1. On this basis, 70 mL/L of methanol corrosion inhibitor and 6 g/L glucose additive were added to form the optimal electropolishing solution.

(2) The most important factor that affects the electropolishing of nickel titanium alloy pipe is voltage as determined through orthogonal experiment. According to the degree of influence, the other factors are polishing temperature, distance between anode and cathode, and polishing time.

(3) The best electropolishing parameters were obtained through single factor experiment as follows: voltage, 18 V; temperature, 18 ℃; distance between cathode and anode, 20 mm; and polishing time, 100 s. Under these parameters, the best surface roughness is 40.7 nm.

(4) The wall thickness of the tube maintains a linear law and decreases after electropolishing. The wall thickness was reduced by 24.9 μm and the material removal rate was 0.249 μm/s after the optimum electropolishing time of 100 s. The microscopic appearance of the nickel titanium alloy pipe was greatly improved. The surface is smooth and bright and defects disappeared after polishing.

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