Effect of Environmentally Friendly Oil on Ni-Ti Stent Wire Using Ultraprecision Magnetic Abrasive Finishing

Jeong Su Kim 1, Sung Sik Nam 2, Lida Heng 2, Byeong Sam Kim 3,* and Sang Don Mun 1,2,*

1 Department of Energy Storage/Conversion Engineering, Jeonbuk National University, 567, Baekje-daero, Deokjin-gu, Jeonju-si 54896, Korea; jeongsu1592@naver.com
2 Division of Mechanical Design Engineering, Jeonbuk National University, 567, Baekje-daero, Deokjin-gu, Jeonju-si 54896, Korea; nam6978@naver.com (S.S.N.); henglida1@gmail.com (L.H.)
3 Department of Smart Automotive Engineering, Wonkwang University, 460, Iksan-daero, Iksan-si 54538, Korea
* Correspondence: anvkbs@wku.ac.kr (B.S.K.); msd@jbnu.ac.kr (S.D.M.); Tel.: +82-63-850-6697 (B.S.K.); +82-63-270-4762 (S.D.M.)

Received: 27 August 2020; Accepted: 28 September 2020; Published: 30 September 2020

Abstract: Nickel-titanium (Ni-Ti) stent wire has been widely used to make shape-memory actuator wire for numerous medical industrial applications, with the result that it frequently comes into contact with the human body. High-quality and nontoxic surfaces of this material are therefore in high demand. We used a rotating magnetic field for an ultraprecision finishing of Ni-Ti stent wire biomaterials and evaluated the finishing technique’s efficacy with different processing oils. To create nontoxic Ni-Ti stent wire, the industrial processing oils that are generally used in the surface improvement process were exchanged for oils with low environmental impacts, and processed under rotating magnetic fields at different speeds and processing times. The processing performance of the different oils was compared and verified. The results show that ultraprecision magnetic abrasive finishing that uses olive and castor oil improves surface roughness by 66.67%, and 45.83%, respectively. SEM and energy-dispersive X-ray spectroscopy (EDX) analyses of the finished components (before and after processing) showed that the material composition of the Ni-Ti stent wire was not changed. Additionally, the magnetic abrasive tool composition was not found on the surface of the finished Ni-Ti stent wire. In conclusion, the environmentally friendly oil effectively improved the diameter of the Ni-Ti stent wire, demonstrating the utility of olive and castor oil in ultraprecision finishing of Ni-Ti stent wire biomaterials.

Keywords: ultraprecision magnetic abrasive finishing (UPMAF); environmentally friendly oil; Ni-Ti stent wire; surface roughness (Ra); removed diameter (RD)

1. Introduction

Nickel-titanium (Ni-Ti) stent wire is a biomaterial, which have been widely used in various applications including medical devices [1–3]. For example, it is used for endovascular stents, which are useful in treating various heart diseases. Blood flow can be improved by inserting a collapsed nickel Ni-Ti stent into a vein and heating the wire, and it can serve as a substitute for sutures. As a result, high-quality surface finishes and mechanical functionality have become desirable characteristics of such biomaterials [4,5]. Conventional polishing or grinding can produce high-quality surfaces [6,7]. In previous works, many researchers have adopted some surface finishing methods for improving the surface accuracy of their products. Chang et al. [8] used the magnetic abrasive finishing process for improving a surface roughness (Ra) of cylindrical SKD11 materials using unbonded magnetic abrasive tools. According to his results, the Ra of cylindrical SKD11 materials was enhanced to 0.042 µm.
by the unbonded magnetic abrasive tools. Heng et al. [9] proposed a new manufacturing precision microdiameter ZrO$_2$ bar 800 µm in diameter using new magnetic pole designs via ultraprecision magnetic abrasive finishing. According to his results, a surface roughness Ra of ZrO$_2$ ceramic bar was enhanced to 0.02 µm within 40 s under the optimal conditions. Singh et al. [10] applied the magnetic abrasive finishing process for enhancing the accuracy of a plane workpiece with various important parameters (i.e., voltage (DC), finishing gap, rotating speed, and abrasive grain size). According to his study, the voltage and working gap are obtained to be the best parameters for a change in surface roughness (ΔRa). However, such techniques typically use industrial processing oils (e.g., light oil, oil mist, SEA oil), which contain toxic substances that are likely to exist on the finished surface [11], reducing the appeal of such products [12]. Park et al. [13] have explained that, in the machining process, when industrial oils such as petroleum-based oils are used, they possibly are more harmful to human health than ecological oils. Benedicto and Carou et al. [14] have reviewed the application of various machining fluids on the machining processes. The machining fluid have been widely used for reducing the machining temperature, and for removing microchips of metal workpieces. Despite these critical works, some disadvantages still remain, such as the environmental impact and health risks to workers. Li and Aghazadeh et al. [15] have studied the health effects associated with the toxicity from metalworking fluids (MWFs) in grinding processes. They have reported that a waste oil, coolant, or another lubricant can generate a toxicity characteristic leachate procedure, which could be effective in human health.

In recent years, a surface accuracy and dimensional accuracy of wire products have been improved by some advanced surface treatment methods (i.e., ion implantation and plasma coating) [16]. The ion implantation and plasma-coating technique have successfully improved the surface quality of some biomedical wire materials (i.e., Ni-Ti wire, TMA wire, beta-titanium wire, etc.) [17]. However, despite the potential advantages of these surface treatment methods, various limitations still exist. In the ion implantation process, some highly toxic gases (i.e., arsine (AsH$_3$), and phosphine (PH$_3$)) have been used [18]. Therefore, these toxic gases probably remain on the wire workpiece surface after processing by ion implantation. Rahman et al. [19] demonstrated that in the plasma coating process, the high voltage electrical shock has been supplied to the gap of electrodes for producing the plasma. Therefore, in order to overcome these problems, the environmentally friendly oils have been applied to the ultraprecision magnetic abrasive finishing (UPMAF) process for ultraprecision finishing of Ni-Ti stent wire. In this study, we evaluated the effectiveness of light oil, olive oil, and castor oil for the UPMAF process of Ni-Ti stent wire in terms of Ra, and removed diameter (RD). This research aims to elucidate the characteristics of Ni-Ti stent wire produced with an UPMAF process and a rotating magnetic field according to different processing oils. In addition, the effects of important input parameters (i.e., the rotating speed of the magnetic field, and different processing times) on Ra and removed diameter were studied in this research.

2. Experimental Method and Setup

A photograph and a schematic diagram of an UPMAF process using a rotating magnetic field for processing Ni-Ti stent wire are shown in Figures 1 and 2, respectively. The equipment comprised a magnetic abrasive finishing part, a spool-driving stepping motor, two driven spools, two fixing rollers, two proximity sensors, a sensor controller, an electric slider, a power supply, a programmable controller, an electrical slider controller, a stepping motor controller, and a stepping motor (speed range: 350–4000 rpm). To achieve a high efficiency of finishing accuracy of a Ni-Ti stent wire, two sets of Nd-Fe-B permanent magnets were used. The permanent magnets were composed of a south pole and north pole, which generated lines of magnetic force between the poles. The mixture for the magnetic abrasive particles consists of electrolytic iron particles, diamond abrasive particles, and processing oil. The abrasive particles were controlled by the magnetic force at room temperature (25 °C). To perform ultraprecision magnetic abrasive finishing, a Ni-Ti stent wire 120 mm in length was inserted inside the particulate brush of the magnetic abrasive tool and vibrated at 10 Hz. The finishing part rotated at
up to 2000 rpm. The schematic view of magnetic force acting on magnetic abrasive particle during the UPMAF process is shown in Figure 3. As the Nd-Fe-B permanent magnets were used, 520-mT of magnetic flux density was obtained in the finishing zone. For the finishing mechanisms of an UPMAF process, “M” is a position, where a magnetic force, \( F_m \), strongly pushes on the Fe particle. A magnetic force, \( F_m \), is generated by the two forces, \( F_x \) on the x-component and \( F_y \) on the y-component. The force \( F_x \) acts on the magnetic abrasive particle along the direction of the line of the magnetic field. The force \( F_y \) is produced by the line of the magnetic field when the Ni-Ti wire material pushes out the bridges formed in the direction of magnetic equipotential lines. A magnetic force, \( F_m \), acting on a magnetic abrasive particle can be expressed by Equations (1) and (2) [20].

\[
\begin{align*}
F_x &= \mu_0 V \left( \frac{dH}{dx} \right) \\
F_y &= \mu_0 V \left( \frac{dH}{dy} \right)
\end{align*}
\]

**Figure 1.** Photograph of ultraprecision magnetic abrasive finishing equipment for an ultraprecision Ni-Ti wire stent.

**Figure 2.** Diagram of ultraprecision magnetic abrasive finishing equipment for an ultraprecision of Ni-Ti wire.

**Figure 3.** Schematic view of magnetic force acting on magnetic abrasive particle.
Where, \( x \) is direction of the line of magnetic field, \( y \) is direction of the magnetic equipotential line, \( \chi_{FP} \) is the material magnetic susceptibility, \( \mu \) is the permeability of free space, \( V \) is the volume of the magnetic abrasive particles, \( H \) is a magnetic field strength at point “M”, \( \frac{dH}{dX} \) and, \( \frac{dH}{dY} \) are the variation rates of magnetic field strength in \( x \) and \( y \) components, respectively.

\[
F_m = F_x + F_y
\]

\[
F_x = \chi_{FP} \mu VH \left( \frac{dH}{dX} \right) \quad \text{and} \quad F_y = \chi_{FP} \mu VH \left( \frac{dH}{dY} \right)
\]

Figure 4 is a photograph of the finishing part of an UPMAF process using a rotating magnetic field for the Ni-Ti stent wire. As shown in Figure 4, the Ni-Ti stent wire workpiece was put the gap between both magnetic poles, and surrounded by a mixture of unbonded magnetic abrasive particles. These magnetic abrasive particles were governed by magnetic forces. To perform an UPMAF process, a workpiece was moved inside the particulate brush of magnetic abrasive particles while the finishing part rotated. With this working procedure, the ultraprecision finishing of Ni-Ti stent wire was achieved.

2.1. Materials

In this study, the workpiece was Ni-Ti stent wire, a biomaterial commonly used in a variety of biomedical applications. The Ni-Ti stent wires were 120 mm in length and 0.5 mm in diameter, with an Ra of approximately 0.24 \( \mu \)m. A 2D dimension view of Ni-Ti stent wire workpiece is shown Figure 5. Figure 6 shows a photograph comparison of Ni-Ti stent wires used in this study. Tables 1 and 2 list the mechanical and chemical compositions of the Ni-Ti stent.
Processing oils are essential elements of the finishing or grinding process, reducing the friction and high temperatures that occur between the surface finish of the sample and the abrasive particles [21]. During the UPMAF process, the mechanical friction between the relative motion of the sample and abrasive particles can cause microcracks on the finished surface. High temperatures generated during the finishing process can increase the wear of the abrasive tools, resulting in dimensional deviation and premature failure. To reduce both friction and temperatures in the finishing process, processing oils are applied to the mixtures of magnetic abrasive tools. In previous research, industrial processing oils have been used in the magnetic abrasive finishing process, but after the finishing process, undesirable toxic substances in the industrial oil are likely to exist on the finished surface, which can also suffer from unacceptable surface roughness. To overcome these problems, we replaced the industrial processing oils commonly used in finishing or machining processes with oil associated with low environmental impacts, including olive, castor, and light oil. A comparison of the properties of the processing oil used for UPMAF process is supplied in Table 3. Light oil has the lowest viscosity and density when compared with olive oil and castor oil, but the highest surface tension (31 dyne/cm), followed by castor oil and olive oil. However, castor oil has the highest viscosity among three oils.

Table 3. Characteristics of processing oil used in the finishing process.

| Processing Oil | Temperature (°C) | Viscosity (Pa·s) | Density (g/cm³) | Surface Tension (dyne/cm) |
|----------------|------------------|------------------|-----------------|--------------------------|
| Castor oil     | 26               | 0.3115           | 0.956           | 14.89 ± 1.12             |
| Olive oil      | 26               | 0.0341           | 0.857           | 10.00 ± 0.66             |
| Light oil      | 26               | 0.005            | 0.8–0.82        | 31                       |

2.2. Typical Processing Oils

Figure 6. Photographic comparison of Ni-Ti stent wire material.

Table 1. Mechanical properties of Ni-Ti stent wire.

| Properties                  | Value of Properties |
|-----------------------------|---------------------|
| Density                     | 6.45 g/cm³          |
| Tensile strength            | 800–1500 MPa        |
| Tensile yield strength      | 100–800 MPa         |
| Poisson’s ratio             | 0.33                |
| Elastic modulus             | 70–110 GPa          |
| Elongation at failure       | 1–20%               |

Table 2. Chemical composition of Ni-Ti wire.

| Element | Spect. | Chemical Element (%) | Atomic |
|---------|--------|----------------------|--------|
| Ti K    | ED     | 44.69                | 50.24  |
| Ni K    | ED     | 55.31                | 49.76  |
| Total   |        | 100.00               | 100.00 |

Characteristics of processing oil used in the finishing process.
2.3. Experimental Conditions

Detailed conditions for this experiment are supplied in Table 4. Ni-Ti stent wires with an Ra of 24 μm were chosen as the sample workpiece and finished at different rotating speeds of the magnetic field (i.e., 500, 1000, 1500, and 2000 rpm), for 150 s of total finishing time. Nd-Fe-B permanent magnets were utilized to generate the high magnetic force. The vibration frequency of the magnetic pole was 10 Hz with an amplitude of 5 mm, and the moving feed of the workpiece was 80 mm/min. Three different processing oils (light, olive, and castor oil) were applied during the process for comparison. Scanning electron microscope microimages were utilized to evaluate the changes in Ra of the Ni-Ti stent wire. For determination of surface roughness after processing, the average surface roughness (Ra) of Ni-Ti stent wire was measured at three different positions every 30 s of processing time by using a surface roughness tester (Mitutoyo SJ-400) (Mitutoyo, Sakado, Japan). Figure 7 shows a measuring procedure of surface roughness Ra value for wire material using a surface roughness tester (Mitutoyo SJ-400). As shown in the photo that during the measuring process, the tip was moved along with the length of wire material and the measuring length on wire sample was 5 mm with the measuring speed was 0.5 m/s. Also, the value of removed diameter of Ni-Ti stent wire was measured every 30 s of processing time by using a laser scan micrometer (Mitutoyo LSM-6200) (Mitutoyo, Sakado, Japan). The photos of the scanning electron microscope (SEM at 120 ×) were used to assess the improvement in Ra of the Ni-Ti stent wire in an UPMAF process using rotating magnetic field.

Table 4. Experimental conditions.

| Parameter                      | Specification                                      |
|--------------------------------|----------------------------------------------------|
| Workpiece material            | Ni-Ti wire stent (L = 250 mm, D = 0.5 mm)          |
| Electrolytic iron powder      | 0.8 g (Fe#200)                                     |
| Diamond paste                 | 0.5 μm (0.3 g)                                     |
| Processing oil                | 0.2 mL (light oil, olive oil, castor oil)          |
| Magnet type                   | Nd-Fe-B permanent magnet (size: 20 × 10 × 10 mm³) |
| Magnetic pole shape           | 1 mm square edge                                   |
| Amplitude                     | 5 mm                                               |
| Workpiece moving feed         | 80 mm/min                                          |
| Rotational speed              | 500 rpm, 1000 rpm, 1500 rpm, 2000 rpm              |
| Processing time               | 0 s, 30 s, 60 s, 90 s, 120 s, 150 s                |
| Frequency                     | 10 Hz                                              |
| Magnetic flux density in finishing zone | 520 mT           |
| Working gap                   | 2.25 mm                                            |

Figure 7. Measuring procedure of surface roughness value for wire material, using a surface roughness tester (Mitutoyo SJ-400).
3. Result and Discussion

To investigate the finishing characteristics of an ultraprecision magnetic abrasive finishing with different processing oils, the electrolytic iron powder (Fe#200) and diamond abrasive particles (0.5 μm) were mixed together with light oil, olive oil, and castor oil. The effect of different processing oils on finishing characteristics of Ni-Ti stent wires at different magnetic field rotating speeds was discussed.

3.1. Effect of Light Oil on Finishing Characteristics

To find the most optimal magnetic field rotating speed in terms of the surface roughness, the experiment was performed at a magnetic field rotating speed (500, 1000, 1500, and 2000 rpm), 10 Hz of vibration frequency, 5 mm of amplitude, and a feed rate of 80 mm/min. The effect of light oil on improvement in surface roughness of the Ni-Ti wire with various rotation speeds of the magnetic field at (500, 1000, 1500, 2000 rpm) is shown in Figure 8. As shown in Figure 8, Ra values of the Ni-Ti wire stent were significantly improved by light oil at all rotation speeds. The greatest improvement in Ra was obtained at 1500 rpm followed by 1000, 500, and 2000 rpm. This indicates that increasing the rotation speed of the magnetic field can improve Ra of an Ni-Ti wire stent. In the case of 1500 rpm, the Ra of the stent wire decreased from 0.24 μm to 0.07 μm over 150 s of processing time. However, at 2000 rpm of magnetic field rotating speed, the centrifugal force of the magnetic abrasive tools was increased, resulting in reduced the magnetic force, and therefore the magnetic abrasive tools flew in all directions.

![Graph showing Correlation of surface roughness Ra vs. processing time](image)

Figure 8. Correlation of surface roughness Ra vs. processing time, (light oil, diameter 0.5 μm, 80 mm/min).

3.2. Effect of Olive oil on Finishing Characteristics

Olive oil is an environmentally friendly substance that is generally utilized in the food and medical industries [22,23]. It has a viscosity of 0.0341 Pa·s, and a density of 0.857 kg/m³. In this study, 0.2 mL of olive oil was combined with 0.8 g of electrolytic iron particles and 0.3 g of diamond paste at 25 °C using an unbonded magnetic abrasive method. The effect of olive oil on improvement in Ra of the stent wire at various rotating speeds of the magnetic field is shown in Figure 9. Olive oil significantly improved the surface roughness of Ni-Ti wire at all rotating speeds. However, 1500 rpm was found to be the optimal condition at 90 s of processing time. When 1500 rpm of rotating speed was used, the original Ra value of Ni-Ti improved from 0.24 μm to 0.07 μm for 90 s, after which the Ra did not improve further, because the unevenness of a surface of Ni-Ti stent wire was completely removed by that time. The slope of 2000 rpm shows worse improvement in Ra compared with the other conditions. The result can be attributed to the increase in the centrifugal force of magnetic abrasive tools.
1000, 1500, and 2000 rpm) is shown in Figure 10. As with the light oil and olive oil, the Ra of the Ni-Ti wire stent improved at all rotating speeds. The slope of 1500 rpm shows the greatest improvement in surface roughness of the Ni-Ti wire workpiece rapidly improves from 0 s to 30 s of processing time, and then improves at a diminished rate until 150 s. The greatest improvement in Ra was obtained with light oil, followed by olive oil, and castor oil. In the case of industrial oil, the Ra value decreased from 0.24 μm to 0.08 μm for 90 s of processing time.

3.3. Effect of Castor Oil on Finishing Characteristics

Castor oil is a colorless vegetable oil pressed from castor beans [24]. The boiling point of castor oil is 313 °C, its viscosity is 0.3115 Pa-s, and its density is 0.956 kg/m³. This oil is commonly utilized in cosmetic products, including creams and moisturizers. In addition, it has been utilized to improve hair conditioning in other products due to supposed antidandruff properties. In this study, 0.2 mL of castor oil was combined with 0.8 g of electrolytic iron particles and 0.3 g of diamond paste. The effect of castor oil on the improvement in Ra of the wire stent at various rotating speeds of the magnetic field (500, 1000, 1500, and 2000 rpm) is shown in Figure 10. As with the light oil and olive oil, the Ra of the Ni-Ti wire stent improved at all rotating speeds. The slope of 1500 rpm shows the greatest improvement in Ra, from 0.24 μm to 0.12 μm for 90 s of processing time.

3.4. Percentage Improvement in Surface Roughness (PIISR)

The effect of different processing oils on the improvement in surface roughness of Ni-Ti stent wire is shown in Figure 11. The processing time of each workpiece was 150 s. In the bar graph, the surface roughness of the Ni-Ti wire workpiece rapidly improves from 0 s to 30 s of processing time, and then improves at a diminished rate until 150 s. The greatest improvement in Ra was obtained with light oil, followed by olive oil, and castor oil. In the case of industrial oil, the Ra value decreased from 0.24 μm to 0.07 μm. With olive and castor oils, Ra values improved from 0.24 μm to 0.08 μm and from 0.24 μm to 0.12 μm, respectively. The percentage of improvement formula for Ni-Ti wire stent Ra as
a function of different processing oils can be expressed by a formula. BUPMAF (before ultraprecision magnetic abrasive finishing) is the Ra value before processing and AUPMAF (after ultraprecision magnetic abrasive finishing) is the value after 150 s of processing. PIISR is the percentage improvement in surface roughness, expressed as the rate of change of Ra for each set of processing conditions as a percentage of the improvement in Ra.

\[
PIISR = \frac{BUPMAF - AUPMAF}{BUPMAF} \times 100\%
\]  

(3)

Figure 11. Correlation of surface roughness Ra vs. processing time according to processing oils, (1500 rpm, 0.5 μm, 80 mm/min).

A PIISR graph of the improvement in surface roughness Ra before and after processing according to processing oil within 150 s of processing time is shown in Figure 12. The results show that improvement in Ra for each processing oil was greater than 45%. Light oil was associated with an improvement of 70.83%, while olive and castor oil resulted in improvements of 66.67% and 45.833%, respectively. Light oil is therefore the preferred oil, followed by olive oil and castor oil. This result can be attributed to the viscosity of the processing oils. As shown in Table 3, the viscosity values of light oil, olive oil, and castor oil 0.3115, 0.0341, and 0.005, respectively. From this it can be concluded that low-viscosity oil produced greater improvements in Ra compared with oils of higher viscosity. Light oil, which has the lowest viscosity and density, reduced the temperature and friction generated during finishing and resulted in a high-quality Ra value. According to the lowest viscosity of light oil (0.005 Pa-s), the Ra value obtained by this condition should be much better than olive oil. However, the Ra value is difficult to improve to 0.07 μm. This is probably due to the effect of another parameter on Ra improvement, such as 0.5 μm of abrasive, which cannot enhance the Ra value less than 0.07 μm.

Figure 12. Correlation of percentage improvement in surface roughness (PIISR) vs. processing time under optimal conditions, (1500 rpm, 150 s, 0.5 μm 10 Hz).
We can conclude that environmentally friendly processing oils can be used for precision finishing of Ni-Ti wire stents via an UPMAF process. Olive oil was chosen as the processing oil for precision finishing of Ni-Ti wire material at 500, 1000, 1500, and 2000 rpm of a rotating magnetic field for 150 s. The effect of olive oil on the removed diameter of Ni-Ti against processing time is shown in Figure 13. The results show that the removed diameter (RD) of Ni-Ti wires can be significantly increased in all conditions of a rotating magnetic field. In terms of the RD, the diameters of the wire materials removed at 500, 1000, 1500, and 2000 rpm were 0.00130, 0.00212, 0.00281, and 0.00192 mm, respectively. As with Ra improvement, 1500 rpm was associated with the largest reduction in diameter. This can be explained by the fact that, at 2000 rpm of rotational speed, the unbonded magnetic abrasive particles have enough time for removing the irregular scratches from the Ni-Ti stent wire’s surface. Therefore, it can be confirmed that, when increasing the rotating speed to a certain level, the best result can be received.

![Figure 13. Correlation of removed diameter vs. processing time (olive oil, 0.5 μm, 80 mm/min).](image)

SEM microimages of Ni-Ti stent wires before and after processing by an UPMAF process (magnified 120 times) are shown in Figure 14. The surface conditions of Ni-Ti stent wires before finishing are shown in Figure 14a. Initial scratches and unevenness were found throughout the surface of the stent wire, and the initial Ra was 0.24 μm. The surface condition of the wire after processing by light oil, olive oil, and castor oil can be found in the Figure 14b–d), respectively. It was confirmed that the finished surfaces of the Ni-Ti wire were smoother than the surface before processing. The surfaces finished with light oil and olive oil were significantly smoother than before processing, with Ra values of 0.07 μm and 0.08 μm, respectively. However, the surfaces finished with castor oil were not as smooth as those finished with light oil and olive oil. As can be seen in Figure 14d, the original scratches and irregular asperities remain on the surface. Energy-dispersive X-ray spectroscopy (EDX) analysis of a wire stent produced by ultraprecision magnetic abrasive finishing with olive oil is shown in Figure 15. The chemical composition of the stent wire before processing is shown in Figure 15a. The analysis result of EDX test shows that 44.60% Ti and 55.40% Ni were detected at the Ni-Ti stent wire surface. After processing with olive oil, 44.69% Ti, and 55.31% Ni were detected at the surface, as seen in Figure 15b. In addition, EDX analysis revealed no toxic substances on the finished surfaces of the Ni-Ti wire.
Figure 14. Surface of the workpiece before and after finishing. (a) Before finishing, $Ra = 0.24 \, \mu m$; (b) Finished with light oil, $Ra = 0.07 \, \mu m$; (c) Finished with olive oil $Ra = 0.08 \, \mu m$; (d) Finished with castor oil $Ra = 0.12 \, \mu m$.

Figure 15. Energy-dispersive X-ray spectroscopy (EDX) test results of Ni-Ti wire before and after processing by ultraprecision magnetic abrasive. (a) Components of the workpiece before processing ($Ra: 0.24 \, \mu m$, processing time: 0 s); (b) Components of the workpiece after processing (light oil, $Ra: 0.08 \, \mu m$, processing time: 120 s).
4. Conclusions

In this research, an UPMAF process using rotating magnetic field was utilized to the high-precision finishing of Ni-Ti stent wire material. Vegetable oil was used as the finishing oil and was compared with the industrial finishing oil that is commonly utilized in the conventional magnetic abrasive finishing process. The characteristics and finishing abilities of these techniques were compared, and the Ni-Ti stent wire workpiece was finished by the different rotational speeds of the magnetic field with vegetable oil as finishing oil, and the following results were shown:

1. To study the characteristics of different processing oils, two types of vegetable oil (olive oil and castor oil) were used and compared with industrial light oil. The improvements in Ra with light oil, olive oil, and castor oil were equivalent to treatment at 0.07 µm, 0.08 µm, and 0.12 µm, respectively. In the cases of light oil and olive oil, the deviation in improvement was not significantly different. Therefore, the industrial oil that has been widely used in the finishing process for Ni-Ti wire can be replaced by olive oil.

2. Light oil, olive oil, and castor oil improved Ra values by 70.83%, 66.67%, and 45.83%, respectively. In each case the improvement was greater than 45.83%. The different results of improvement in surface roughness Ra can be explained based on the different value of the finishing oil’s viscosity. As the lowest viscosity is that of light oil (0.005 Pa·s), the Ra value obtained by this condition should be much better than olive oil. However, the Ra value is difficult to improve to 0.07 µm. This is probably due to the effect of another parameter such as 0.5 µm of abrasive on Ra improvement, which cannot enhance the Ra value less than 0.07 µm.

3. In terms of the removed diameter, environmentally friendly oil can reduce the diameter of Ni-Ti stent wires by 0.00281 mm after 150 s while improving the surface roughness Ra from 0.24 µm to 0.08 µm. This can be confirmed that an ultraprecision magnetic abrasive finishing process with environmentally friendly oil can reduce the surface roughness value and diameter of Ni-Ti stent wire simultaneously.

4. Olive oil exhibited excellent performance in terms of Ra and removed diameter. An EDX analysis found no components of the processing oil and or toxic substances on the surface finish of the Ni-Ti stent wire, indicating that olive oil can be applied to ultraprecision surface finishing.

Author Contributions: Design experiment, methodology and conceptualization J.S.K. and L.H.; investigation and editing, S.S.N., B.S.K. and S.D.M.; writing of paper, J.S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by NATIONAL RESEARCH FOUNDATION (NRF) of Korea in 2019, (Research Project No.2016R1D1A1B03932103, 2019R1F1A1061819).

References

1. Guo, Y.; Klink, A.; Fu, C.; Snyder, J. Machinability and surface integrity of Nitinol shape memory alloy. *Cirp Ann.* 2013, 62, 83–86. [CrossRef]

2. Duerig, T.; Pelton, A.; Stöckel, D. An overview of nitinol medical applications. *Mater. Sci. Eng. A* 1999, 273, 149–160. [CrossRef]

3. Shabalovskaya, S.; Anderegg, J.; Van Humbeeck, J. Critical overview of Nitinol surfaces and their modifications for medical applications. *Acta Biomater.* 2008, 4, 447–467. [CrossRef] [PubMed]

4. Shabalovskaya, S.; Rondelli, G.; Rettenmayr, M. Nitinol surfaces for implantation. *J. Mater. Eng. Perform.* 2009, 18, 470–474. [CrossRef]

5. Hassel, A.W. Surface treatment of NiTi for medical applications. *Minim. Invasive Ther. Allied Technol.* 2004, 13, 240–247. [CrossRef]

6. Heng, L.; Kim, Y.J.; Mun, S.D. Review of Superfinishing by the Magnetic Abrasive Finishing Process. *High Speed Mach.* 2017, 3, 42–55. [CrossRef]

7. Heng, L.; Yin, C.; Han, S.H.; Song, J.H.; Mun, S.D. Development of a New Ultra-High-Precision Magnetic Abrasive Finishing for Wire Material Using a Rotating Magnetic Field. *Materials* 2019, 12, 312. [CrossRef]
8. Chang, G.W.; Yan, B.H.; Hsu, R.T. Study on cylindrical magnetic abrasive finishing using unbonded magnetic abrasives. *Int. J. Mach. Tools Manuf.* 2002, 42, 575–583. [CrossRef]

9. Heng, L.; Kim, J.S.; Tu, J.F.; Mun, S.D. Fabrication of precision meso-scale diameter ZrO2 ceramic bars using new magnetic pole designs in ultra-precision magnetic abrasive finishing. *Ceram. Int.* 2020. [CrossRef]

10. Singh, D.K.; Jain, V.K.; Raghuram, V. Parametric study of magnetic abrasive finishing process. *J. Mater. Process. Technol.* 2004, 149, 22–29. [CrossRef]

11. Yin, C.; Heng, L.; Kim, J.; Kim, M.; Mun, S. Development of a New Ecological Magnetic Abrasive Tool for Finishing Bio-Wire Material. *Materials* 2019, 12, 714. [CrossRef] [PubMed]

12. Amini, S.; Baraheni, M.; Esmaeili, S.J. Experimental comparison of MO40 steel surface grinding performance under different cooling techniques. *Int. J. Lightweight Mater. Manuf.* 2019, 2, 330–337. [CrossRef]

13. Park, K.H.; Olortegui-Yume, J.; Yoon, M.C.; Kwon, P. A study on droplets and their distribution for minimum quantity lubrication (MQL). *Int. J. Mach. Tools Manuf.* 2010, 50, 824–833. [CrossRef]

14. Benedicto, E.; Carou, D.; Rubio, E.M. Technical, economic and environmental review of the lubrication/cooling systems used in machining processes. *Procedia Eng.* 2017, 184, 99–116. [CrossRef]

15. Li, K.; Aghazadeh, F.; Hatipkarasulu, S.; Ray, T.G. Health risks from exposure to metal-working fluids in machining and grinding operations. *Int. J. Occup. Saf. Ergon.* 2003, 9, 75–95. [CrossRef] [PubMed]

16. Jabbari, Y.S.A.; Fehrman, J.; Barnes, A.C.; Zapf, A.M.; Zinelis, S.; Berzins, D.W. Titanium nitride and nitrogen ion implanted coated dental materials. *Coatings* 2012, 2, 160–178. [CrossRef]

17. Krishnan, M.; Saraswathy, S.; Sukumaran, K.; Abraham, K.M. Effect of ion-implantation on surface characteristics of nickel titanium and titanium molybdenum alloy arch wires. *Indian J. Dent. Res.* 2013, 24, 411–417. [CrossRef]

18. Vavilov, V.S. Possibilities and limitations of ion implantation in diamond, and comparison with other doping methods. *Physics-Uspekhi* 1994, 37, 407–411. [CrossRef]

19. Rahman, M.; Haider, J.; Hashmi, M.J. Health and Safety Issues in Emerging Surface Engineering Techniques. *Compr. Mater. Process.* 2014, 8, 35–47.

20. Djavanroodi, F. Artificial neural network modeling of surface roughness in magnetic abrasive finishing process. *Res. J. Appl. Sci. Eng. Technol.* 2013, 6, 1976–1983. [CrossRef]

21. Yara-Varón, E.; Li, Y.; Balcells, M.; Canela-Garayo, R.; Fabiano-Tixier, A.S.; Chemat, F. Vegetable oils as alternative solvents for green oleo-extraction, purification and formulation of food and natural products. *Molecules* 2017, 22, 447. [CrossRef] [PubMed]

22. Kala, P.; Pandey, P.M. Comparison of finishing characteristics of two paramagnetic materials using double disc magnetic abrasive finishing. *J. Manuf. Process.* 2015, 17, 63–77. [CrossRef]

23. Jain, V.K. Magnetic field assisted abrasive based micro-/nano-finishing. *J. Mater. Process. Technol.* 2009, 209, 6022–6038. [CrossRef]

24. Alfred, T.; Matthäus, B.; Fiebig, H.J. Fats and fatty oils. In *Ullmann’s Encyclopedia of Industrial Chemistry*; Wiley-VCH: Weinheim, Germany, 2000; pp. 1–84.