An investigation into the effects of polishing on surface hardness and corrosion of orthodontic archwires

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Abstract: The purpose of this study was to investigate the effect of surface roughness on the relative corrosion rates of wires of four alloys—stainless steel, nickel titanium, cobalt chromium, and beta titanium. Batches of wire were divided into two groups. Wires in one group were industrially polished to provide a uniform surface finish; wires in the other group were left for comparison "as received." Wire diameter, hardness, and relative corrosion rates were compared within groups before and after polishing. Comparisons were also made across the four groups of alloys. The samples of as-received wires showed variations in surface finish, with beta titanium having the roughest appearance and cobalt chromium the smoothest. Nickel titanium and stainless steel surfaces were similar. Polishing provided a more uniform finish, but significantly reduced the diameter of the wires. Microhardness testing of wire surfaces of each alloy indicated that no significant work-hardening occurred as a result of polishing. The relative corrosion rates (expressed in terms of corrosion current density) in a 0.9% sodium chloride solution were estimated using the electrochemical technique of polarization resistance. Nickel titanium wires exhibited the greatest corrosion current density in the as-received state. Polishing significantly reduced the corrosion rate of nickel titanium, such that comparison between the four alloys in the polished state revealed no significant difference in their relative corrosion rate/corrosion current density.

Key Words: Orthodontic alloys, Polishing, Corrosion

All metals corrode to some degree in every environment. In the oral cavity, orthodontic appliances are subjected to both physical and corrosive damage, which act in combination to degrade physical properties and increase the potential for failure. The rate of this combined damage is of particular interest when considering the life span of appliances, so any method that reduces corrosion would be beneficial.

The by-products of corrosion should also be considered, particularly those of nickel-containing alloys, due to their role in allergic reactions.[1,2] Of particular concern are the allergenic effects of metals and their corrosion by-products in sensitized individuals.

Four alloys are widely used as orthodontic archwires: stainless steel, nickel titanium, cobalt chromium, and beta titanium. All have been used in implants, and investigations have shown all four to be subject to corrosion, particularly in the presence of wear.[3-5]

Investigations of the relative corrosion rates of orthodontic archwires have produced conflicting results, attributed in part to the quality of surface finish.[6,7] Mueller and Chen[8] found that beta titanium wires exhibited good resistance to breakdown, as did cobalt chromium, whereas stainless steel and nickel titanium wires showed a pitting type of corrosive attack.

In order to investigate the relative corrosion rates of the alloys without the influence of varying surface roughnesses, it is necessary to polish the wires to a uniform finish. Polishing, however, can work-harden the surface of metal, and that can affect the corrosion rate.

Schwaninger et al.[9] examined the

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effects of long-term immersion on the properties of nickel titanium wire by immersing samples in 1% sodium chloride for periods of up to 11 months. They found that wires polished in their laboratory (and hence free from surface defects) showed no corrosion. These findings suggest that the ability of nickel titanium to resist corrosive attack is impaired by manufacturing defects in the surface.

Kusy et al.[10] investigated surface roughness of wires of different alloys using laser spectrometry. Test materials were ranked in the following order (from smoothest to roughest): stainless steel > cobalt chromium > beta titanium > nickel titanium. In a comparison of frictional resistances, Garner et al.[11] noted that stainless steel provided significantly less frictional resistance than nickel titanium or beta titanium. Examination of the surface features using scanning electron microscopy suggested that variations in surface roughness accounted for some of the difference in frictional resistance between materials. Obviously, the material and surface of the bracket are also important factors with regard to frictional resistance. Stannard et al.[12] examined archwire materials under both dry and wet conditions and found that beta titanium and stainless steel wires against stainless steel brackets exhibited the lowest friction under both conditions, with values for dry conditions lower than wet.

The relative hardness of archwire and bracket materials affects the degree of wear that will occur. Mueller and Chen[8] compared the hardness of wire surfaces of various orthodontic alloys using the Knoop microhardness test with a 1 kg weight for a period of 20 seconds and found that stainless steel proved to be the hardest, followed by cobalt chromium, beta titanium, and nickel titanium.

The aims of this investigation were fourfold:

1. Examine the surface roughness of four different orthodontic archwires: stainless steel, cobalt chromium, nickel titanium, and beta titanium.
2. Assess their relative corrosion rates before and after polishing.
3. Measure the diameter changes that occurred as a result of the polishing procedure.
4. Measure the hardness of the wire surface of each alloy in as-received and polished states, and determine whether work hardening occurred as a result of polishing.

Materials and methods

Orthodontic wire of four alloys (straight lengths, nominally 0.016 inch diameter) were examined:

1. Stainless steel (A.J. Wilcox Australian Wire, Special Plus, TP Orthodontics, Orthomax, Bradford, UK), 30 x 10 inch lengths
2. Cobalt chromium (Blue Elgiloy, Rocky Mountain Orthodontics, Hudson Ltd, Sheffield, UK), 30 x 14 inch lengths
3. Beta titanium (TMA, Ormco Corp, Optident, Bingley, UK), 10 x 10 inch lengths
4. Nickel titanium (Nitanium, Ortho Organizers, Inc, Precision Orthodontics, Esher, UK), 20 x 7 inch lengths

Diameter measurements

Wire segments were numbered at each end for identification. Diameters were measured at 10 random points using a digital micrometer (accurate to the nearest 0.001 mm). The micrometer was preset to zero before each batch was tested, and the zero reading was checked at random intervals.

The wires were then cut in half. Half of each wire segment was polished, and the diameter of the polished segments was measured in the same way. These values were compared with the original values to assess dimensional change.

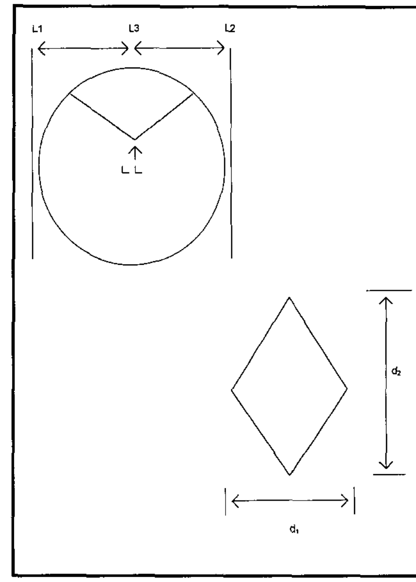

Figure 1
Points recorded for calculation of hardness

Polishing technique

Wires were polished in a centrifugal tumbling machine (FT 4-6, Centrifugal Tumbling Machine, Dr.-Ing. Manfred Dreher GmbH and Co, KG Engelsbrand, W. Germany) with the drums rotating at sufficient speed to create a centrifugal force pressing the contents against the wall. The drum was counter-rotated to produce a soft sliding motion, thus avoiding heavy impact that might have damaged the wires. The polishing process involved three stages[13]:

- Wet cutting—using ceramic balls with fine silica flour for a period of 2.5 hours
- Deburring—using a walnut granulate and aluminum oxide cutting compound paste for 2 hours
- Dry polishing—using a nut polishing granulate with barrel polishing paste and a form of paraffin for the final 2 hours

Examination of the wire surfaces

Wire surfaces from both the as-received and polished groups were examined using light and electron microscopy. Three specimens of each archwire material, chosen at random, were examined under an electron microscope using a magnification of X150. The surfaces were described based on subjective visual analysis of the frequency of surface irregularities.

Hardness testing

Twenty hardness recordings were made from each alloy group using a Leitz microhardness tester (Leitz Miniload 2 Micro Hardness Tester for Vickers, Knoop and Scratch Hardness) with a Vickers diamond. The hardness tester was precalibrated to provide an indentation time of 15 seconds, which is in accordance with the BSI guidelines 5411.[14]

Each wire was mounted on a jig that held the wire at two points using a screw and washer attachment. A strip of double-sided tape between the washers helped hold the wire flat against the base and prevent rolling upon indentation.

The position of the lateral aspects of the wire, as viewed under low power, was recorded and the central point of the wire was calculated (Figure 1). Before indenting, the focus was adjusted under high power objective to ensure the correct distance between the diamond tip and the sample to be tested. The test weight provided a loading force of 9.81 newtons for a set period of 15 seconds.

The diagonals (d_1 and d_2) of the diamond indent were measured to the nearest 0.1 micrometer under the high power objective. The Vickers hardness number (HV) was calculated by first determining the arithmetic mean of the two measured diagonals, then using the following formula:[14, 15]

$$HV = \frac{189 \times F \times 10^3}{d^2}$$

where F = the force used to indent (in newtons), 189 = Vickers constant, and d = the arithmetic mean of the two diagonals in micrometers.

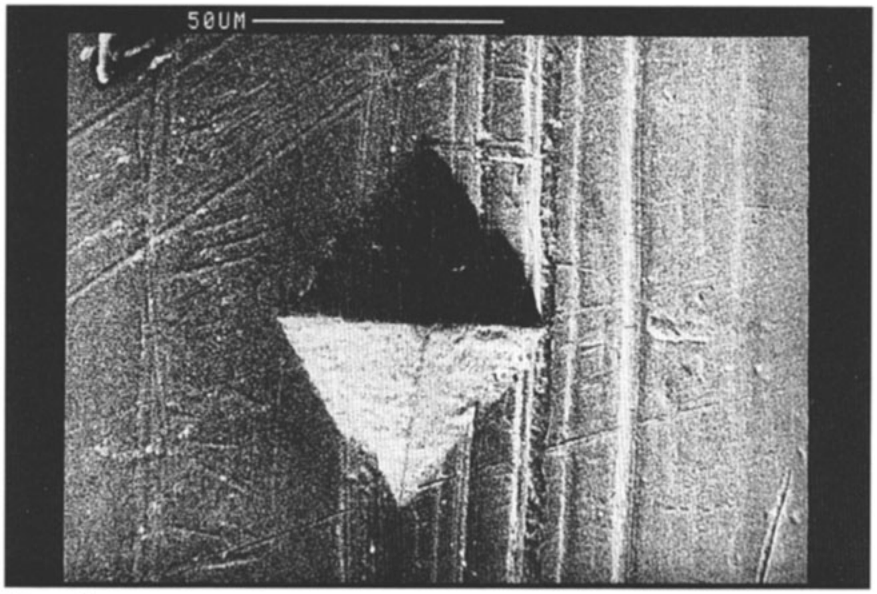

Figure 2

Scanning electron micrograph of Vickers indent in a cobalt chromium wire surface

The surface curvature of the wire introduced an error in determining the hardness that could lead to falsely elevated readings. To compensate for this error, correction factors were used as designated in the International Standards ISO 6507/2.[15] The correction factor was dependent on the ratio of the mean value of the diagonal of the indent to the diameter of the wires.

Corrosion testing

The corrosion testing equipment comprised a Model 175 universal programmer (EG and G Princeton Applied Research, Wokingham, Berks, UK), Model 363 potentiostat (EG and G Princeton Applied Research, Wokingham, Berks, UK), K47 corrosion cell (EG and G Princeton Applied Research, Wokingham, Berks, UK), a Houston 2000 chart recorder, an Avometer, a Grant water bath, high density graphite counter electrodes, Vicor tip and saturated calomel electrode, sodium chloride 0.9%(0.9% Sodium Chloride Intravenous Infusion BP, Baxter Healthcare, Thetford, UK) and oxygen-free nitrogen. The equipment was tested for function and accuracy by measuring the resistance of a test resistor.

The corrosive medium, 0.9% sodium chloride solution, is recommended in the ASTM Standard F746.[16] The cell was immersed in a waterbath at 37ºC, and the solution was purged with oxygen-free nitrogen for 30 minutes to provide an anaerobic solution at a constant temperature and to prevent localized polarization around the test wire.

Specimen preparation

The wires were cleaned by immersion in toluene for 5 minutes, then rinsed in distilled water and allowed to dry. After cleaning, they were handled only with college tweezers. Each wire specimen was held by a screw in the working electrode assembly. To prevent corrosion of the working electrode, the metal surface was coated with vinyl polysilane.

Calculation of the corrosion rate

Because the equivalent weights of the alloys were not known, the aim of the study was to determine relative, rather than absolute, corrosion rates. Thus, the corrosion rate could be expressed in terms of the

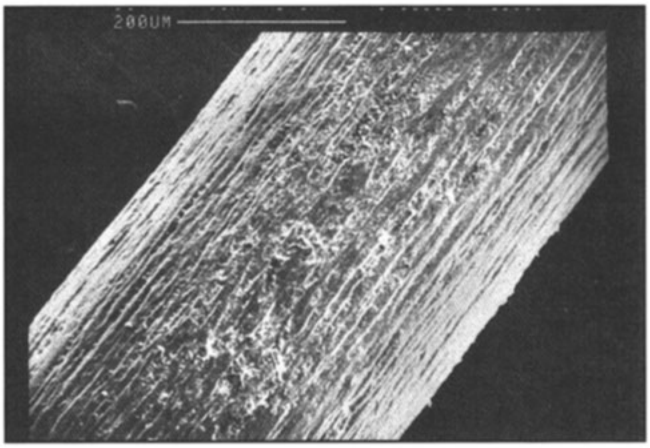

Figure 3
As-received beta titanium (SEM)

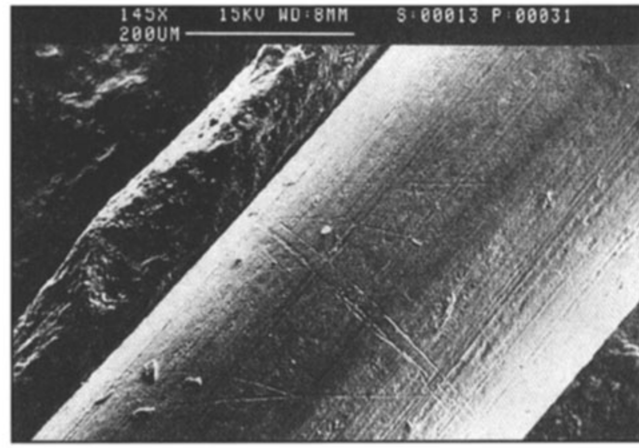

Figure 4
As-received stainless steel (SEM)

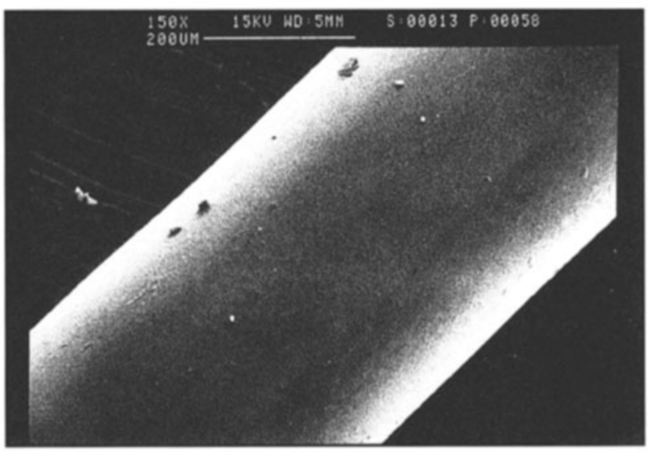

Figure 5
Polished beta titanium (SEM)

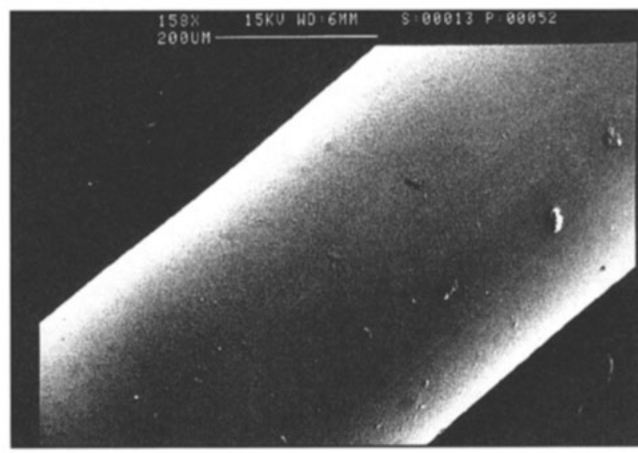

Figure 6
Polished stainless steel (SEM)

corrosion current density (I_{corr}). Each system has a characteristic potential known as the corrosion potential (E_{corr}), and the current present in this system is known as the corrosion current (i_{corr}). The corrosion current cannot be measured directly and must be calculated using the following formula:[17,18]

$$i_{corr} = \frac{\beta_A \beta_C}{2.3(\beta_A + \beta_C)} \frac{[\Delta i]}{[\Delta E]}$$

where $\Delta E / \Delta i$ = the slope of the polarization resistance plot (which is resistance from Ohm's Law), and β_A β_C = the anodic and cathodic Tafel constants.

This study assumed Tafel constants of 0.1 V decade $^{-1}$:

Therefore, the corrosion current

$$i_{corr} = \frac{0.0217}{R}$$

and the corrosion current density

$$I_{corr} = \frac{0.0217}{R_p}$$

where R_p = resistance / surface area, known as polarization resistance.

Linear polarization technique

Each wire segment was placed in the corrosion cell for 1 hour to allow the wire to stabilize according to the ASTM Standard F746.[16] The corrosion potential (E_{corr}) was recorded from the avometer, the polarity being the opposite of that shown.[19] This potential with the opposite polarity was set on the potentiostat. The Model 175 programmer was set to allow a scan of ±30 mV across the corrosion potential, and this output signal summed with the value of the corrosion potential was applied to the test wire at a scan rate of 1 mV second-1. The scan run time was 60 seconds.

The chart recorder plotted the corrosion current against the overvoltage, thus producing a slope from which the corrosion current density I_{corr} was calculated.

Error of the method

Diameter measurements

To assess the measurement error, random points were marked on wire lengths. The diameter was recorded on two occasions 1 week apart. To assess the measurement error, 10 replicate readings were taken. The error was assessed by calculating the standard deviation of the differences between repeated readings using Dahlberg's formula:[20]

$$S = \frac{\sqrt{\sum d^2}}{2n}$$

where S = standard deviation of the differences, d = difference between each pair of double determinants, and n = number of double determinants.

Hardness testing

Thirty-five of the diamond indents were remeasured to assess the error involved in recording the diagonals and subsequent error in hardness calculations. To determine if the error was random, the mean was plotted against the difference from each pair of readings.

Statistical analysis

After checking the groups for normal distribution using a normal probability plot, the results of the diameter and hardness recordings were analyzed using the Mini-Tab (MiniTab Statistics Program, Minitab Inc, State College, Penn, USA) program. For comparison between groups with respect to wire diameter, the paired *t*-test was used. For comparison of hardness figures, the unpaired *t*-test was used because the recordings were taken at random. The results of the corrosion investigations were analyzed using the SAS statistics program (SAS Institute Inc, Cary, NC, USA). A one-way analysis of variance between the alloy groups was performed.

Conventional levels of significance were used: p=0.05, nonsignificant; p<0.05, weakly significant, marked *; p<0.01, significant, marked **; p<0.001, highly significant, marked ***.

Results

The results are shown in Tables 1 through 4.

Table 1
Wire diameters before and after polishing

Wire alloy	Range of mean diameters, as-received group (mm)	Range of mean diameters, polished group (mm)	Diameter change following following polishing
Stainless steel	0.402 - 0.405	0.384 - 0.391	*** ($p < 0.001$)
Cobalt chromium	0.394 - 0.397	0.380 - 0.390	*** ($p < 0.001$)
Nickel titanium	0.398 - 0.406	0.390 - 0.401	*** ($p < 0.001$)
Beta titanium	0.405 - 0.409	0.391 - 0.395	*** ($p < 0.001$)

*** Highly significant

Surface appearance

Using subjective visual analysis, the as-received beta titanium was the roughest wire (Figure 3), followed by stainless steel (Figure 4) and nickel titanium. Both stainless steel and nickel titanium wires demonstrated longitudinal grooving as a result of being drawn through diamond dies during production. Stainless steel also showed areas of circumferential grooves. The cobalt chromium wire appeared to be the smoothest, but it did have occasional deep longitudinal grooves, again from the drawing process. The polished wires were almost featureless, even under the electron microscope (Figures 5 and 6). Of the eight polished specimens mounted under the electron microscope, only one (beta titanium) showed traces of the original surface defect.

Diameter testing

In the as-received group, the largest diameters were obtained from beta titanium wire (0.405 to 0.409 mm) and the smallest from cobalt chromium (0.394 to 0.397 mm). The range of mean diameters for as-received nickel titanium and stainless steel were 0.398 to 0.406 mm and 0.402 to 0.405 mm, respectively. Polishing reduced the diameters of wires of all four alloys (p<0.001).

Hardness testing

Hardness recordings are shown in Table 2. Stainless steel was found to be the hardest alloy (mean value 601.8 HV1), and beta titanium the least hard (mean value 355.9 HV1). There was no significant change in hardness following polishing.

Corrosion

The results of the corrosion experiments are shown in Tables 3 and 4. Table 4 shows that polishing had no significant effect on corrosion rate for stainless steel or beta titanium. However, it significantly reduced the corrosion rate of nickel titanium and significantly increased the corrosion rate of cobalt chromium.

Analysis of variance between groups showed that in the as-received group, nickel titanium corroded significantly faster than the other three alloys. In the polished group, there was no significant difference between alloys.

Errors

Diameter of wires

From the diameter recordings, *s* was found to be 9.80×10^{-4} mm.

Hardness

Calculation of the measurement error showed the standard deviation of the differences between repeated recordings to be 13.50 HV1. To determine if the error was random, the mean was plotted against the difference for each pair of readings. The distribution of the resulting plot was random.

Table 2
Vickers Hardness for as-received and polished wires

Wire alloy	As-received Mean	As-received SD	Polished Mean	Polished SD	*t*-value	DF	*p*	95% confidence interval	
Stainless steel	601.8	26.9	601.6	22.1	0.03	36	0.98	-15.6 to 16.0	NS
Cobalt chromium	435.0	25.6	437.3	11.7	0.37	26	0.72	-15.2 to 10.5	NS
Nickel titanium	438.6	15.9	446.7	22.0	1.33	34	0.19	-20.4 to 4.2	NS
Beta titanium	355.9	16.9	354.9	6.5	0.25	24	0.81	-7.4 to 9.4	NS

Unit of measurement for hardness values = HV1

Discussion

Surface appearance

This study found that the as-received beta titanium wire was the roughest, followed by stainless steel and nickel titanium, both of which demonstrated longitudinal grooving. The cobalt chromium wire was the smoothest, but it still had some deep longitudinal grooves. The polished wires were all relatively featureless, as shown in Figures 5 and 6.

Diameter testing

Measurement of the wire diameters revealed variations in wire size across the as-received groups. The largest diameters were for beta titanium, followed by stainless steel, nickel titanium, and cobalt chromium. Similar variations in wire dimensions were recorded by Waters et al.[21,22] and Brown.[23]

The tolerance acceptable for orthodontic wires is outlined in the British Standard Specification 3507.[24] For wires of a nominal diameter of 0.406 mm, the range of acceptable diameters is ±0.012 mm (0.394 mm to 0.418 mm). All the wires measured were within the limits of the tolerance specified.

The results showed that a highly significant but variable reduction in diameter occurred in all four groups as a result of polishing ($p < 0.001$).

All the wires were polished by the same process for the same period of time, so the relative dimensional loss may be an indication of resistance to wear. The amount of surface loss was not reflected in the comparative hardness of the alloys; stainless steel, which suffered the greatest loss, proved to be the hardest wire, while nickel titanium, with the least wear, ranked second, equal to cobalt chromium.

Table 3
Values of I_{corr} for pairs of as-received and polished wires

Alloy	As-received Mean	As-received SD	Polished Mean	Polished SD
Stainless steel	172.98	153.78	142.65	261.24
Cobalt chromium	32.73	39.76	65.26	13.30
Nickel titanium	838.92	187.63	118.00	863.43
Beta titanium	38.57	19.86	33.30	27.15

Units: $nAcm^{-2}$

Table 4
Analysis of difference between I_{corr} values for as-received and polished wires

Alloy	W-value	Prob < W	Signed rank	Prob > S	95% confidence interval
Stainless steel	0.913	0.3327	3.5	0.7344	-136 to 196
Cobalt chromium	0.830	0.0452	19.5	0.0195	-64.8 to -0.291
Nickel titanium	0.775	0.0075	27.5	0.0020	220 to 1220
Beta titanium	0.967	0.8824	3.0	0.6875	-30.6 to 41.1

Hardness testing

Stainless steel had the hardest surface at 601.8 HV1, followed by nickel titanium at 438.6 HV1, cobalt chromium at 435.0 HV1, and beta titanium at 355.9 HV1. Polishing proved to have no significant effect on the hardness of each alloy ($p > 0.1$) at the depth of indentation used (Table 2). Mueller and Chen[8] found stainless steel wires to be the hardest at 646 HKN, followed by cobalt chromium (green Elgiloy) at 471 HKN, beta titanium at 317 HKN, and nickel titanium at 303 HKN. The results of this investigation showed a similar ranking, with the exception of nickel titanium. This difference is probably attributable to differences in the brands used. Unfortunately, the results cannot be compared directly because both the Knoop and Vickers hardness values are arbitrary and, therefore, not interchangeable.

The polishing process did not significantly work-harden any of the alloys, but it did slightly reduce the degree of scatter in the results.

Corrosion

As expected, the relative corrosion rates showed a wide degree of scatter, with corrosion current values being extremely small. The corrosion current densities calculated were of a magnitude of $10x^{-9}Acm^{-2}$.

The results showed that polishing had no effect on the corrosion rates of stainless steel or beta titanium, but did lead to a significant reduction in the corrosion rate of nickel titanium. Cobalt chromium exhibited a significant increase following polishing. The as-received nickel titanium corroded significantly faster than the other three alloys. In the polished group, no significant difference was seen across the alloys.

The corrosion potentials recorded showed a wide degree of scatter from the four alloy groups, both in the as-received and polished groups, although polishing did reduce the scatter. The mean values and standard deviations found in this study were within the same range as those reported by Hoar and Mears[25] and Mueller and Chen.[8]

Polishing nickel titanium reduced the corrosion rate significantly ($p<0.01$), which supports the findings of Schwaninger et al.,[9] that corrosion is due to defects in the surface finish produced during manufacture. For stainless steel and beta titanium, no significant difference was found between the polished and as-received groups. Again, the scatter of the results was so large that any small changes in the relative corrosion rates could have been obscured. The opposite findings appeared when the two cobalt chromium groups were compared, with polishing increasing the corrosion rate. This outcome may have been due to inadequate repassivation of the metal following polishing.

The corrosion potential of stainless steel tended to fluctuate, which is in accordance with the work of Hoar and Mears.[25] The corrosion potential of the other three alloys appeared stable. The lack of reproducibility of corrosion rates for stainless steel wires has been shown by Greene and Saltzman.[26] Variations may be due to differences in microstructure and composition within the same wire, as differences in the draw rate of stainless steel during manufacture causes variations in grain size and shape, which can affect corrosion.[27]

Conclusions

1. Surface roughness varied between orthodontic wires, with beta titanium having the roughest surface appearance.
2. Polishing provided a uniform surface finish for the alloys, but significantly reduced the wire diameters.
3. No significant difference was found between the hardness of the as-received and polished groups, indicating that the polishing process did not work-harden the metal.
4. Nickel titanium in the as-received state corroded faster than the other three alloys.
5. Polishing reduced the corrosion rate of nickel titanium.

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