European Journal of Orthodontics 31 (2009) 260–265
doi:10.1093/ejo/cjn104
Advance Access publication 2 February 2009

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Morphological characterization of as-received and *in vivo* orthodontic stainless steel archwires

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SUMMARY This study was undertaken to evaluate the material degradation of clinical bracket-archwire-contacting surfaces after *in vivo* orthodontic use. Twenty-four stainless steel multiloop edgewise archwires with two different cross sections (0.016 × 0.016 and 0.016 × 0.022 inches) were used for at least 6 months in the mouths of 14 patients. The surfaces of both as-received (cross-section of 0.016 × 0.016, 0.016 × 0.022, and 0.017 × 0.025 inches) and the *in vivo* wires were examined using scanning electron microscopy.

The as-received wires exhibited an inhomogeneous surface with different surface irregularities resulting from the manufacturing process. For the *in vivo* archwires, an increase in the variety, type, and number of surface irregularities were observed. Crevice corrosion occurred not only at surface irregularities formed during manufacturing and orthodontic handling but also at the bracket-archwire-contacting surfaces and at the archwire surfaces coated with plaque and food remnants. This corrosion may be linked to the formation of a micro-environment at these locations. In addition, a limited number of signs of degradation induced during *in vivo* testing due to wear and friction were observed.

Introduction

Stainless steel (SS) archwires remain popular because of their low cost and excellent formability, along with good mechanical properties (Kapila and Sachdeva, 1989; Brantley, 2001). The SS alloys used as orthodontic wires are of the '18-8' austenitic type that contain approximately 18 per cent chromium and 8 per cent nickel and are classified by the American Iron and Stainless Steel Institute as AISI type 304 (Park and Shearer, 1983; Barrett *et al.*, 1993; Oh *et al.*, 2005).

The surface topography of an orthodontic wire is an essential functional property known to influence the mechanical characteristics, the aesthetic result, the corrosion behaviour, and/or the biocompatibility of devices. The resulting surface structure depends on the alloy used, the complex manufacturing processes, and the surface finish treatment (Burstone and Goldberg, 1980; Bourauel *et al.*, 1998; Neumann *et al.*, 2002; Pernier *et al.*, 2005).

The exact composition is commonly not clearly mentioned in the information made available by manufacturers of orthodontic SS compounds and, more importantly, no information is given on the manufacturing process. Despite this lack of information, SS wires are often considered as a reference material for comparing the characteristics of other types of orthodontic wires such as nickel titanium (Verstrynge *et al.*, 2006).

Biocompatibility is a complex and rapidly evolving research area that may seem beyond the scope of the practising orthodontist. However, biocompatibility should be of concern to every practitioner because these issues have profound ethical, social, technical, and legal implications on dental practice, for example the corrosion resistance of orthodontic wires determines their biocompatibility (Huang, 2003).

Orthodontic materials have to withstand physical, mechanical, and biological assaults in the patient's mouth and must be biocompatible in that aggressive environment (Bourauel *et al.*, 1998). Degradation can even be accelerated when mechanical, chemical, or electrochemical processes take place simultaneously. Material degradation products from brackets and/or archwires are then released into the oral environment (Waterhouse, 1984). This complex process is called 'tribocorrosion'. Such a degradation process can have serious clinical implications, ranging from a loss of dimension resulting in a lower force applied to the teeth, to stress corrosion failure of the appliance. In addition, the undesired production of toxic corrosion products in the surrounding tissues is possible (Toms, 1988; Eliades *et al.*, 2004b).

Corrosion in orthodontics has been investigated using a variety of experimental set-ups (Michelberger *et al.*, 2000; Berradja *et al.*, 2006a,b). However, those studies adopted *in vitro* approaches that have some disadvantages. Such tests are accelerated and it is recognized that storage media, consisting of electrolyte or acidic solutions employed *in vitro*, cannot reliably simulate the oral environment. Orthodontic alloys in the mouth are in contact with a variety of substances that impose potent effects on their reactive status and surface integrity, such as saliva that may contain acids arising from the degradation and decomposition of food, environmental factors, and the oral flora and its by-products (Eliades and Athanasiou, 2002). No *in vivo* studies appear to have been undertaken on the alteration of material properties of used or retrieved archwires.

The aim of this research was to investigate the surface topography of as-received SS archwires and to determine the material degradation on clinical bracket-archwire-contacting surfaces after *in vivo* orthodontic treatment. The main attention was focused on the surfaces of the SS archwires after approximately 6 months of *in vivo* function.

Materials and method

Materials

As-received SS wires. Twenty as-received SS orthodontic archwires (3M Unitek, Monrovia, California, USA) with three different cross-sections, 0.016 × 0.016, 0.016 × 0.022, and 0.017 × 0.025 inches, were evaluated.

In vivo SS wires. Twenty-four SS multiloop edgewise archwires (3M Unitek) with two different cross sections, namely 0.016 × 0.016 and 0.016 × 0.022 inches, were used during orthodontic treatment of 14 patients in contact with edgewise SS brackets (Microloc, GAC Inc., Bohemia, New York, USA; Mini Diamond, Ormco, Orange, California, USA) with a 0.018 × 0.025 inch slot size. The archwires were evaluated morphologically after debonding. The archwires functioned for at least 6 months in the oral environment of the patients.

Experimental procedure

The surface of the as-received and *in vivo* tested SS wires were examined using scanning electron microscopy (SEM; FEG-Philips XL-30, Philips Company, Eindhoven, The Netherlands) equipped with energy dispersive X-ray analysis (EDAX). Surface characteristics are reported based on a visual evaluation of the surface irregularities. The magnifications used were ×200, ×500, ×1000, ×2000, and ×5000.

Cleaning procedure

The as-received and used SS archwires were first ultrasonically cleaned at 60°C for 15 minutes with an alkaline solution (VR 6334-16, Henkel, Brussels, Belgium), to remove fats and organic debris, and rinsed with distilled water. Subsequently, the samples were ultrasonically cleaned at 60°C for 15 minutes with sulphuric acid (4 per cent) to remove anorganic debris (e.g. calculus), rinsed with distilled water, and finally dried with ethanol (naturalized ethanol + 5 per cent diethyl ether) in warm air.

As-received SS wires. Samples of the three sizes of archwires were marked at two spots on the four sides of each wire to identify the area to be investigated. This was performed with a diamond pin. SEM images were taken before and after cleaning to investigate the influence of the cleaning procedure on the surface structure of the archwires. Standardization of the tested location and orientation of the sample were possible as a result of the reference marks.

In vivo SS wires. After debonding of the fixed appliance, reference marks were made on the mesial and distal border of each wing at the buccal side of the archwire before removal of the brackets. After removal, these reference marks were extended to the other three sides to localize the bracket-archwire-contacting surfaces (Figure 1).

The wires were cleaned according to the cleaning procedure, attached to specific specimen holders, and SEM images were taken of the four sides.

Results

Surface features of as-received SS wires

The most common archwire patterns noticed during SEM analyses are summarized in Figure 2a-c. Each specimen appeared to have its own characteristic surface structure.

Grooves and striations parallel to the long axis of the archwire (Figure 2a) resulted from the archwire drawing process. Such surface defects were visible on all archwires, while scratches, not parallel to the long axis of the archwire (Figure 2b), were observed on some samples. These can be related to an occasional mechanical impact during manufacturing, for example handling during cutting or holding with instruments. Pitting was the third type of pattern noticed (Figure 2c), which resulted from a chemical interaction, for example pickling or corrosion during manufacturing. Finally, surface defects due to plastic deformation were also detected.

Surface features of in vivo SS wires

Before cleaning of the retrieved archwires, a large amount of plaque and food remnants around the bracket position

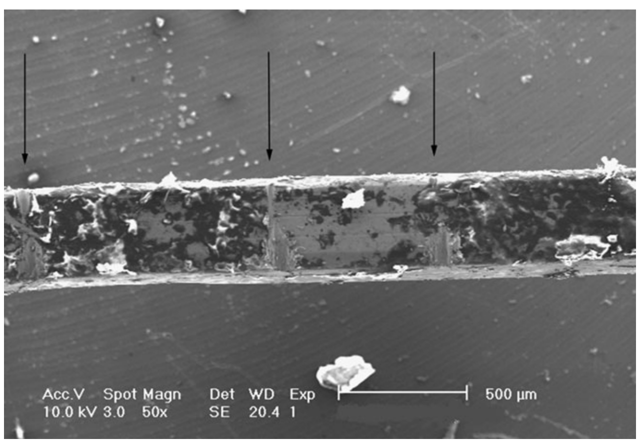

Figure 1 Scanning electron photomicrograph showing plaque and food remnants on an *in vivo* tested archwire before cleaning. Reference marks (arrows) indicate the external border of one of the bracket wings.

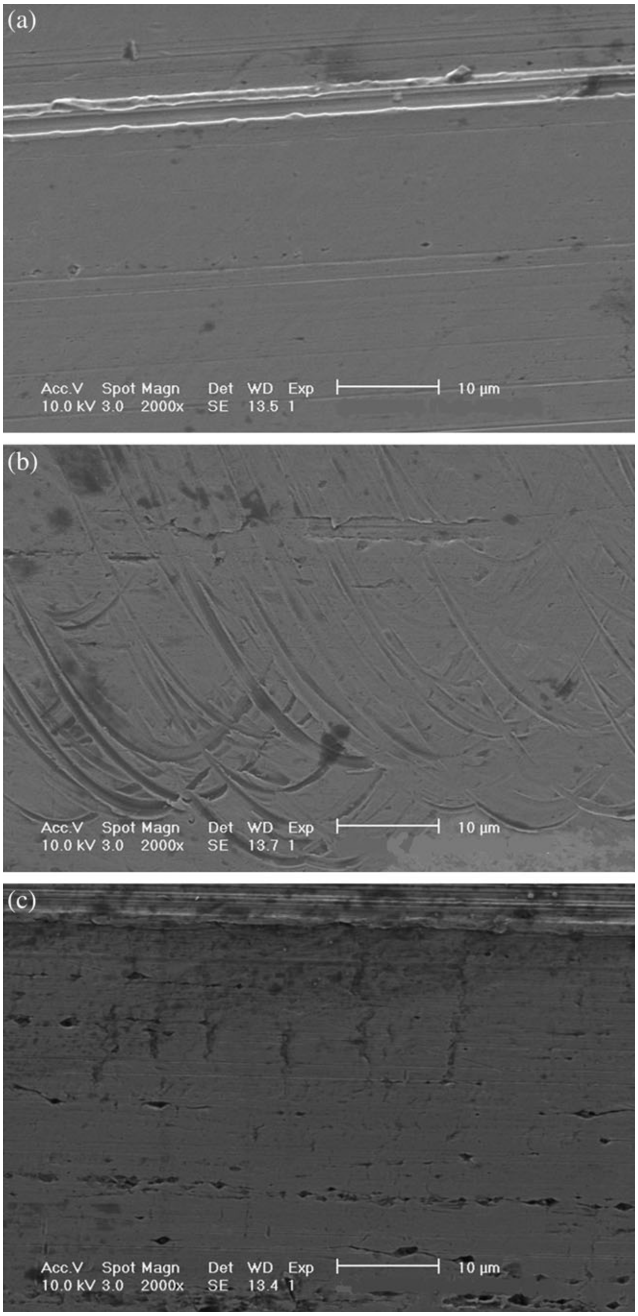

Figure 2 Scanning electron photomicrographs of as-received stainless steel archwires showing (a) grooves and striations parallel to the long axis, (b) scratches not parallel to the long axis, and (c) pits.

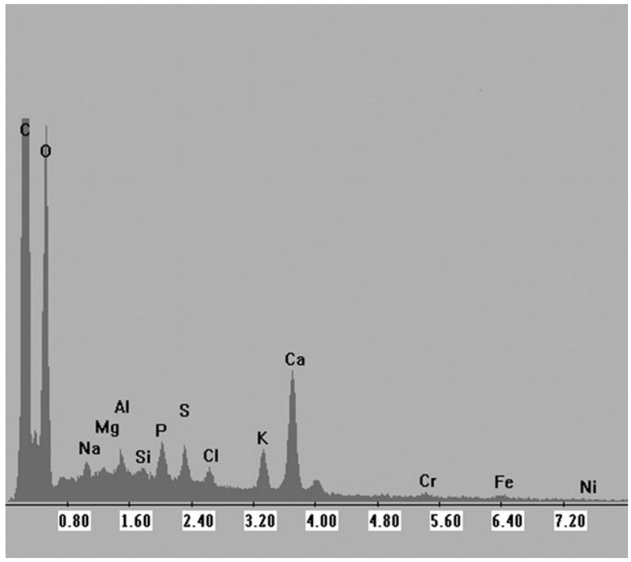

Figure 3 Chemical composition of the debris on an *in vivo* tested archwire before cleaning. Al, aluminium; C, carbon; Ca, calcium; Cl, chlorine; Cr, chromium; Fe, iron; K, potassium; Na, sodium; Ni, nickel; Mg, magnesium; O, oxygen; P, phosphorus; S, sulphur; and Si, silicon.

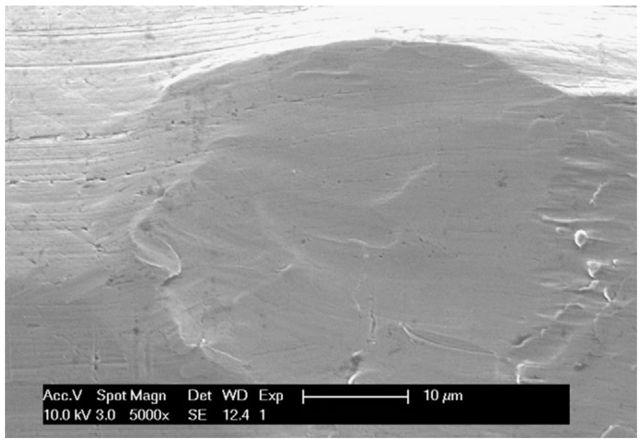

Figure 4 Scanning electron photomicrographs showing plastic deformation at the border of an *in vivo* tested archwire caused by the pressure of an orthodontic plier.

were found (Figure 1). Figure 3 depicts the results from the SEM–EDAX analyses of the debris on an *in vivo* archwire before cleaning. The analyses showed the presence of organic and anorganic compounds.

SEM images of the *in vivo* archwires taken after cleaning revealed an increase and great variety in the type and number of surface irregularities generated by handling during orthodontic treatment. Large differences in the number of surface defects were noticed on the four sides of a given sample and also between samples. Handling with orthodontic pliers caused plastic deformation on surfaces and at the borders of the archwires (Figure 4). The force applied with the orthodontic plier can be so large that cracks may form. Fractured particles can form debris that becomes reattached at different locations on the archwires. Some irregularities were caused during manufacturing and others during handling by the orthodontist. Some photomicrographs showed an image of the border of an archwire exhibiting plastic deformation intersecting parallel grooves. This indicates that grooves formed during the drawing manufacturing process were present before plastic deformation took place.

SEM also revealed crevice corrosion at irregularities caused not only by orthodontic treatment (Figure 5) and the manufacturing process, but also at the bracket–archwire contact areas.

On one sample, a wear track caused by friction at the interface between the bracket and archwire was found (Figure 6).

Discussion

The biocompatibility of a material is related to the characteristics of the passive film present at the surface of materials. Chromium in SS forms a thin and adherent Cr_2O_3-based passive layer that provides corrosion resistance by blocking the diffusion of oxygen to the underlying bulk alloy (Eliades and Athanasiou, 2002; Lin *et al.*, 2006). A minimum of 12 per cent chromium is required to impart the necessary corrosion resistance (Kusy, 1997). This factor is of prime importance for the biological behaviour of materials. Alterations of that passive layer make the material prone to corrosion (Hunt *et al.*, 1999; Kim and Johnson, 1999; Eliades *et al.*, 2004a).

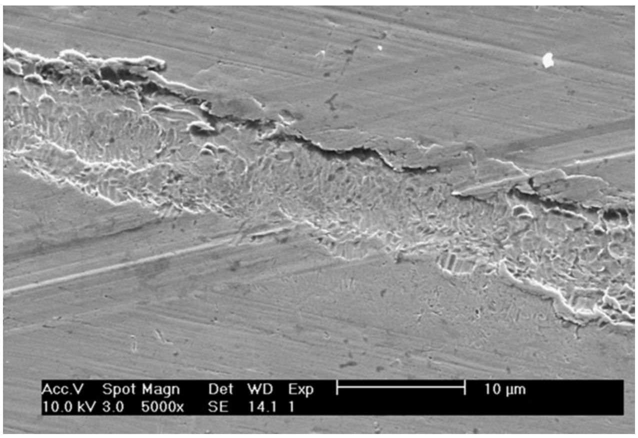

Figure 5 Crevice corrosion on an *in vivo* tested archwire in a groove caused by orthodontic pliers.

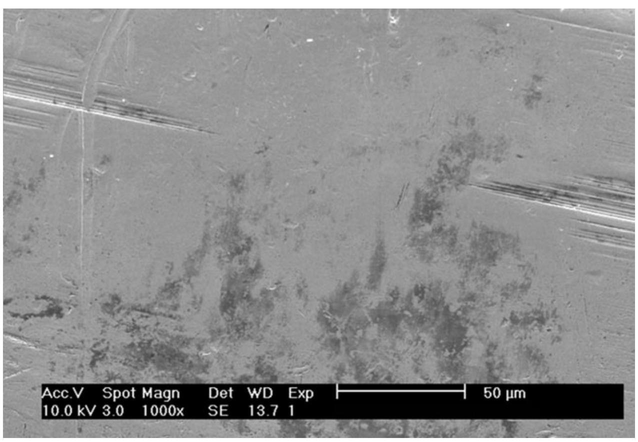

Figure 6 Scanning electron photomicrograph showing a wear track caused by friction.

In this study, the as-received samples showed surfaces with different mechanical irregularities, caused by the manufacturing processes. *In vivo* testing revealed an increase of surface defects on the archwires resulting from handling during orthodontic treatment.

All these surface irregularities alter the passive layer making the archwires less resistant to corrosion. SEM demonstrated the occurrence of crevice corrosion not only at irregularities formed during manufacturing or orthodontic treatment, but also at the bracket-archwire-contacting surfaces due to a gradient in oxygen across these areas (Figure 5). In addition, the archwire surfaces were coated by plaque and food remnants that mask the alloy surface topography to varying extents depending on the individual patient's oral environment and on the intra-oral exposure period. The microbial by-products and metabolic processes may alter the conditions of the micro-environment and decrease the pH. This decrease of pH contributes to the initiation of the corrosion process by disturbing the regeneration of the passive chromium oxide layer (Eliades and Athanasiou, 2002; Landolt, 2006).

Corrosion contributes to the release of foreign substances, namely metallic ions, in the oral cavity. This release of ions may be locally and systematically distributed and can play a role in the aetiology of oral and systemic pathological conditions (Hunt *et al.*, 1999; Geurtsen, 2002). The ions released from SS alloys are mainly iron, nickel, and chromium. Although all three elements may have adverse effects, nickel has received most attention due to its reported potential to produce allergenic (Oh and Kim, 2005), mutagenic (Lee *et al.*, 1998), cytotoxic (Wataha *et al.*, 1997), or carcinogenic (Lewis and Sunderman, 1996) effects.

The other material problem related to the use of an orthodontic archwire and bracket is frictional behaviour (Oh *et al.*, 2005). Loreille (2002) claimed that one of the main reasons for the unpredictable control of orthodontic forces may be the surface corrosion of wires and brackets. The presence of a third body, such as wear debris or corrosion products at the interface between bracket and archwire, can alter the initial friction contact conditions (Al-Khatib *et al.*, 2005). Only one sample of the investigated *in vivo* archwires exhibited a wear track caused by repeated loading in the elastic zone (Figure 6). One explanation could be the small contact area between the archwire surfaces and the bracket caused by the difference in dimension, 0.016 × 0.016 and 0.018 × 0.025 inches, respectively. Another explanation could be the use of SS archwires in the finishing phase of orthodontic treatment when sliding is no longer present, or that low forces were used creating stresses in the contact area below the yield stress so that plastic deformation did not occur.

SEM showed that each wire had its own surface characteristics, with a great variation in the type and number of surface defects on the four sides of each sample, and also between different samples of both the as-received and *in vivo* tested archwires. This depends on different factors such as the manufacturing processes, the time in the mouth, the activities of the orthodontist, and the habits of the patient (Maijer and Smith, 1982; Neumann *et al.*, 2002). Information about the processing of the wires is proprietary to each manufacturer and is not available (Verstrynge *et al.*, 2006). Nevertheless, this investigation revealed a large number of mechanical and chemical irregularities present on as-received unused archwires.

In this investigation, the archwires were cleaned with an alkaline solution to remove fat and organic debris followed by sulphuric acid to remove inorganic debris from the surface of the archwires. Sulphuric acid is currently used not only in industrial cleaning but also in sanitary home products. Sulphuric acid can cause some etching of the SS surface when used for long periods at a certain concentration. In this study, the concentration of the sulphuric acid and the duration of cleaning were too low and too short to produce such hazardous effects on the microstructure of the surface of the samples. The cleaning procedure used did not affect the topography of the archwire.

Unfortunately, in this study, as SEM images of the *in vivo* archwires before the start of orthodontic treatment were not available, no distinction could be made between surface irregularities caused by handling during the manufacturing processes and those caused during orthodontic treatment. This study also focused only on SS archwires and not on SS brackets. Further investigations will extend knowledge on these matters.

Conclusions

In this research, the surface topography of as-received orthodontic SS archwires as well as archwires after *in vivo* use was examined. SEM revealed the presence on archwires of mechanical surface irregularities caused not only during manufacture but also by handling during orthodontic treatment, as well as mechanical interactions between archwire and bracket and chemical interactions between the archwire and oral environment.

Crevice corrosion occurs not only at surface defects but also at bracket-archwire-contacting surfaces as well as at archwire surfaces coated with plaque and food remnants. A gradient in oxygen across these areas is most probably the origin of this degradation process.

In addition, limited signs of degradation due to wear and friction resulting from *in vivo* use were also noticed. A fretting process might cause this degradation process.

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Acknowledgement

The authors would like to thank Rudy De Vos and Professor Marc De Bonte (MTM-KULeuven) for their support.

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