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## CORROSION DAMAGE INVESTIGATION OF SILVER-SOLDERED STAINLESS STEEL ORTHODONTIC APPLIANCES USED IN VIVO

### OCENA ZNISZCZEŃ KOROZYJNYCH UŻYWANYCH IN VIVO STAŁYCH APARATÓW ORTODONTYCZNYCH O POŁĄCZENIACH LUTOWANYCH NA BAZIE SREBRA

Processes of destruction of products used in orthodontic treatment, e.g. fixed orthodontic appliances, microimplants or dental prostheses considerably limit its operational lifetime and comfort and safety of patients. The objective of the research was to evaluate and assess corrosion damage to silver-soldered stainless steel rapid palatal expansion Hyrax devices. Used in vivo for 2 or 6 months, respectively, RPE (rapid palatal expansion) devices were analyzed macroscopically and in a scanning electron microscope with an energy X-ray analyzer for signs of corrosion. The evaluated appliances showed discernible differences between the overall condition of the noble solders and the stainless steel elements. The Ag-rich solders were chiefly covered in corrosion pits, whereas stainless steel wires, molar bands and Hyrax screws presented corrosion-free surfaces. What is more, the EDS analysis showed differential element composition of the solders. According to the results, noble materials, such as Ag-rich solders, can corrode in a salivary environment when coupled with stainless steel. The selective leaching processes are observed.

*Keywords:* corrosion, fixed orthodontic appliances, dental materials, noble solder, silver solder

Procesy niszczenia produktów wykorzystywanych w leczeniu ortodontycznym, takich jak: stałych aparatów ortodontycznych, mikroimplantów oraz elementów protetyki stomatologicznej znacząco skracają trwałość eksploatacyjną wyrobów gotowych oraz obniżają komfort leczenia i poziom bezpieczeństwa pacjentów. Celem pracy jest ocena zniszczeń korozyjnych powstałych podczas eksploatacji wykonanych ze stali nierdzewnej stałych aparatów ortodontycznych typu Hyrax przeznaczonych do poszerzania szczęki na skutek tzw. szybkiej ekspansji podniebienia. Używane in vivo od 2 do 6 miesięcy aparaty RPE (rapid palatal expansion) przeanalizowano makroskopowo, za pomocą skaningowego mikroskopu elektronowego oraz przy użyciu rentgenowskiego spektroskopu dyspersyjnego.

Analiza uzyskanych wyników wyraźnie wskazuje na różnicę w ogólnym stanie pomiędzy elementami wykonanymi ze stali nierdzewnej i lutami na bazie srebra. Połączenia lutowane we wszystkich analizowanych aparatach uległy dostrzegalnemu makroskopowo roztwarzaniu korozyjnemu, natomiast części konstrukcyjne wykonane ze stali 316L, takie jak: śruby, druty oraz pierścienie trzonowe wolne były od korozji. Co więcej, wykonana analiza składu chemicznego połączeń lutowanych wykazała nierównomierne rozłożenie pierwiastków stopowych, wskazujące na występowanie korozji selektywnej. Wyniki zrealizowanych badań wskazują, iż w połączeniu ze stałą nierdzewną w środowisku jamy ustnej możliwe jest roztwarzanie korozyjne materiałów szlachetnych, jakimi są luty srebrne. Obserwuje się ślady zachodzących procesów selektywnego roztwarzania korozyjnego o szczególnie wysokiej intensywności na granicy stal nierdzewna – lut na bazie srebra.

## 1. Introduction

Removable orthodontic appliances are generally made from wires of stainless steel, cobalt-chromium alloys, nickel-titanium or  $\beta$ -titanium [1], used one at a time or in combination, and may have soldered joints to obtain the proper and reliable construction of the appliance [1-2]. More particularly, austenitic stainless steels, containing approximately 18% chromium and 8% nickel, are one of the most popular metallic materials in orthodontics [1-3]. The combination of their good

mechanical properties, relatively low cost of manufacturing, good corrosion resistance in the salivary environment and soldering ability [2] has led to their employment in a wide range of applications, e.g., orthodontic brackets and molded devices. Typical stainless steel orthodontic appliances, e.g., rapid palatal expansion Hyrax devices, are commonly soldered with low fusing silver solders [2, 4].

However, the soldering of stainless steel orthodontic appliances is not without technical difficulties. Firstly, no union is created between the solder and the steel, and as

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a result the solder, under the tough conditions occurring in the oral environment considering stress load in conjunction with the destructive action of oral secretions, is prone to come away from the steel, leading to device breakage [5]. What is more, heating stainless steel to the temperature required for soldering causes steel annealing, making it ineffective in spring purposes of the designed device [5]. Post-soldering heat treatment does not restore alloy elasticity. As a result, it affects the tensile strengths of the orthodontic silver-soldered stainless steel joints [2]. Furthermore, it has been proven that the presence of soldered joints causes greater susceptibility to corrosion [6]. The phenomenon of corrosion in the oral cavity is described as a complex electrolytic occurrence of total or partial degradation of an alloy, leading to the release of ions [7]. Corrosive dissolution can be caused by numerous factors, e.g., surface finish [8], internal stresses [9], pH [10], temperature [10-11] and composition of the immersion solution, soldering and thermal treatment [7]. Moreover, in the literature there is a lack of data on the actual performance of silver-soldered stainless steel joints in orthodontic applications, in terms of either oral health or mechanical strength [7].

The aim of the conducted study was to evaluate corrosion damage in silver-soldered stainless steel rapid palatal expansion Hyrax appliances.

## 2. Materials and methods

Two silver-soldered stainless steel rapid palatal expansion appliances were investigated after *in vivo* application. The devices were worn intraorally for two and six months (Fig. 1, Fig. 2), respectively. In order to remove organic debris, the samples were rinsed in room temperature ethyl alcohol in an ultrasonic cleaning machine (InterSonic, IS-2). The appliances were examined and photographed in a scanning electron microscope (Hitachi S-3000N). Concentrations of the alloys elements were determined by using energy-dispersive X-ray spectroscopy (Thermo Scientific NORAN 4460D-1UUS-SN instrument).

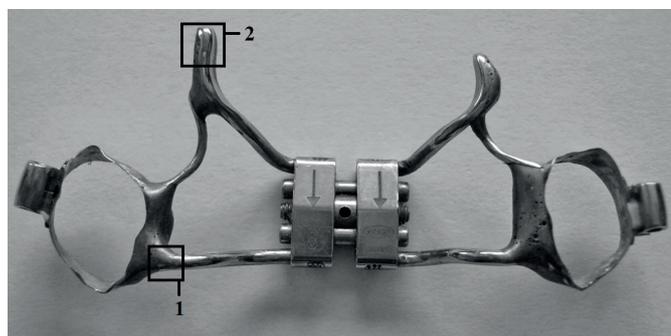


Fig. 1. The Hyrax device used for 2 months; 1, 2 – described in the text solders

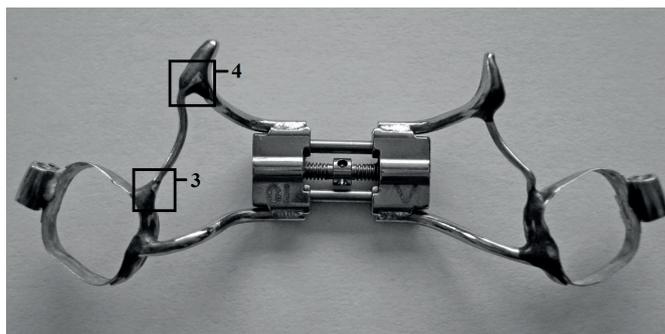


Fig. 2. The RPE appliance used intraorally for 6 months; 3, 4 – mentioned in the text solders

## 3. Results and discussion

Both macroscopic and SEM analyses of the devices' overall surfaces showed a discernible difference between the solders and the stainless steel elements surface condition, though they were in service for 6 months maximum. In both RPE appliances, the stainless steel wires, Hyrax screws and molar bands were only marked chiefly with scratches. On the contrary, orthodontic devices solders were covered in macroscopically visible corrosion pits.

EDS analysis of the wires and molar bands of both appliances, expressed in weight percent (wt%) and rounded to the nearest integer, revealed a Fe/Cr/Ni ratio of approximately 70/19/9, which is characteristic for 316 stainless steel (Table 1). As the report shows, Hyrax screws were made of 316L stainless steel (Table 1), whereas all solders were made of Ag-Cu-Zn noble alloy (Table 2).

TABLE 1  
EDX analysis (wt.%) of the various parts of examined devices

Element	Si	Cr	Mn	Fe	Ni	Mo
<b>Wires</b>	1	18	1	71	8	-
<b>Molar bands</b>	1	20	-	69	10	-
<b>Hyrax screw</b>	1	18	2	66	11	3

TABLE 2  
EDX analysis (wt.%) of selected solders

Element	Cu	Zn	Mo	Ag
<b>Solder 1, RPE 2 months</b>	13	16	2	70
<b>Solder 2, RPE 2 months</b>	14	15	3	68
<b>Solder 3, RPE 6 months</b>	10	14	2	74
<b>Solder 4, RPE 6 months</b>	9	14	2	74

It is worth noting that solders of the RPE appliance after 6 months in service reveal lower Cu and Zn mass content than samples used intraorally for 2 months (Table 2). What is more, linear EDS analysis (Fig. 4) of solder 1 showed differential elements composition in the material interface. Corrosion pits were singled out as Cu-rich areas, whereas their zinc amount was remarkably reduced. The Ag content remained at an almost even level.

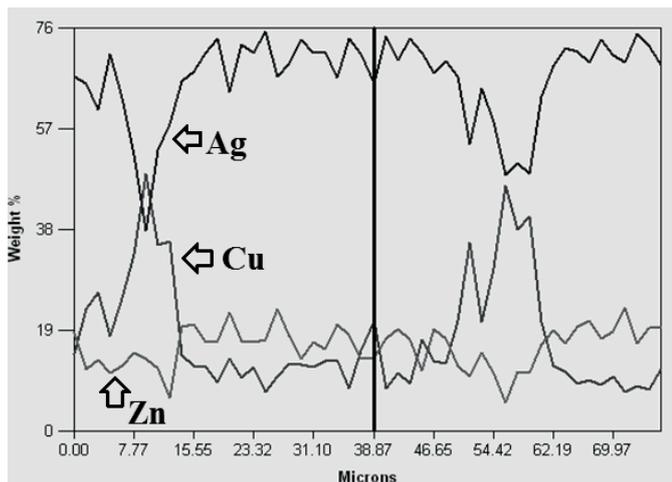


Fig. 3. Linear EDS analysis of solder 1

It was observed that corrosion damage was considerably greater in appliances used for 6 months rather than 2 months (Fig. 4, Fig. 5, Fig. 6). Unlike appliances used for a shorter amount of time, solders of the Hyrax expansion device after 6 months in service showed a predisposition to come away from the steel (Fig. 6). This might cause immediate failure of the appliance and a premature need to repair the device.

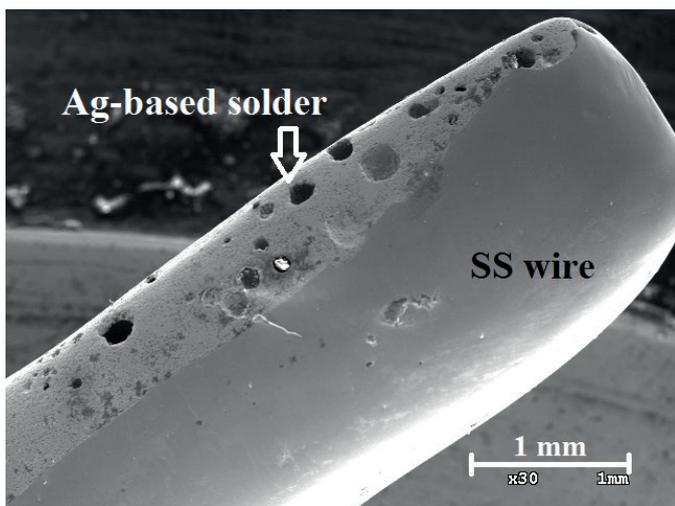


Fig. 4. RPE appliance after 2 months in service, solder 2, magnification 30×, SEM photograph. Visible severe corrosion pits in the solder material and non-corroded wire

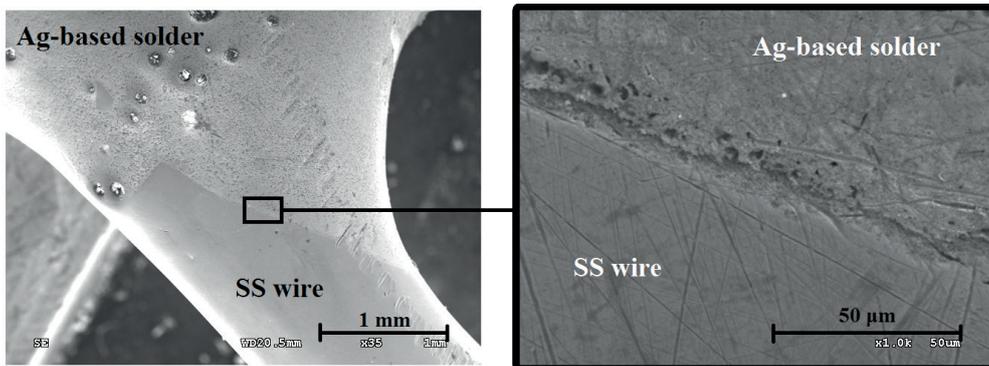


Fig. 5. Hyrax expansion device after 2 months of use, solder 1, magnification 30× (a) and 1000× (b), SEM photographs. Solder shows no tendency to coming away from the steel, although at the magnification of 1000× there is a noticeable characteristic for galvanic corrosion pitted boundary between the materials

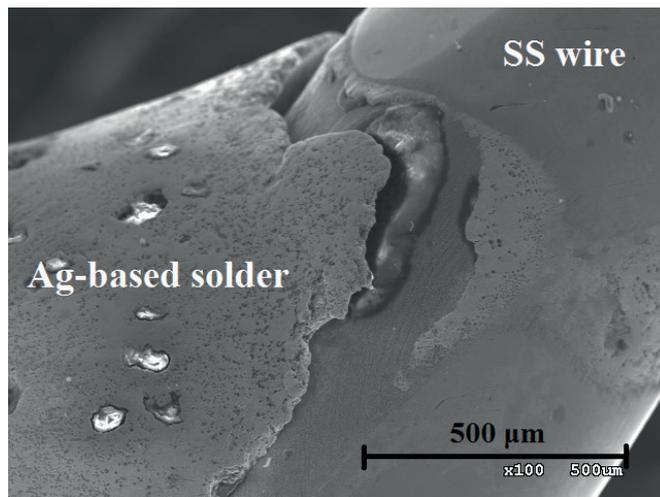


Fig. 6. Hyrax device after 6 months of intraoral use, solder 3, magnification 100×, SEM photograph. Observable tendency to loosening up the bimetallic junction caused by solder corrosion

Corrosion resistance of orthodontic alloys is an important factor for technicians and orthodontists to consider when choosing the proper material for a planned application. Even though the effects of oral corrosion are often imperceptible [12-13], mainly because the allowed dietary intake is not exceeded [3, 14], the presence of an excessive amount of metallic ions in the oral environment may cause some acute conditions [1, 12], including severe adverse reactions to orthodontic alloys [15]. According to Wataha [15], documented allergies have been reported not only for nickel, cobalt or chromium, but also for mercury, copper, gold, palladium, tin, and zinc.

It must also be remembered that the initial material quality is as important as its further processing. Overheating, not encasing the joint completely in the solder, and simply inappropriate construction of the junction, may lead to premature failure of the device [5].

Considering the essence of the corrosion phenomenon, it may seem obvious that the less noble material, which in this case is stainless steel, should be the one to be severely attacked. According to Zinelis et al. [16], silver soldering alloys introduce galvanic coupling with stainless steel alloys, which results in releasing from the Ag-Cu-Zn solder copper and zinc. This process, triggered by higher solder reactivity, may be additionally intensified when the composition of the material unveils preferential dissolution of some elements [2].

In linear EDS analysis (Fig. 3), the examined corrosion pitted solders showed local variations of chemical composition. A similar preferential dissolution of silver solder, containing 22% Cu, 17% Zn, 56% Ag and 5% Sn, has been observed by Vahed et al. [10]. It is known that one-element rich particles result in a micro-galvanic effect, which leads to selective corrosive damage development. Vahed et al. [2] suggest that corrosion processes nucleation is expected to occur first at the stainless steel interface due to the heat-sink effect of the stainless steel and the heterogeneous sites provided by the pre-existing surface, as shown in Fig. 5b.

In this case, the elements which could be released to the human body in corrosion processes are copper, silver and zinc. The constitution of corrosion pits and their relatively small Ag weight percentage might imply that silver is the corroding element, but, according to Vahed et al. [2], Cu-rich areas are most likely to be the origin of corrosion attack, resulting in copper selective leaching. Even though Ag and Zn ions are not thought to be harmful [7, 15], Cu<sup>2+</sup> is known for its mutagenic properties [15] and ease to corrode [8]. It has been proven that in human saliva copper is the most intensively dissolving element from silver solders [7]. According to Syverud et al. [17], alloys containing greater amounts of copper present greater toxicity than low copper alloys. What is more, in vitro studies conducted recently have shown the ability of copper to initiate oxidizing events that may interfere with important cell activities [7]. Manzl et al. [18] conducted a laboratory study on copper toxicology using trout hepatocytes. It has been observed that the presence of copper, induced by calcium loss, causes a consequent loss of liver cell viability.

Health implications are not the only aspects which should be investigated when discussing material corrosion. The mechanical properties of the whole construction advance in degradation, even if one of the parts fails. Insecure, non-springy processes, or coming away from the steel solders, may be unable to provide a reliable interlink between the elements, even for as short an amount of time as 6 months. Nowadays, as an alternative to thermal conjoining procedures, ultrasound laser welding procedures have been introduced [19].

#### 4. Conclusion

The following conclusion was drawn from the results: noble materials such as silver alloys can selectively corrode in saliva when coupled with stainless steel. The dealloying

processes are intense and lead to severe damage, like loosening of soldered joints in a short amount of time. Due to the observed damage, the authors suggest further studies into ultrasound laser welding in orthodontic applications.

#### Acknowledgement

This scientific work was supported by the Faculty of Mechanical Engineering, Bialystok University of Technology, project No MB/WM/13/2014.

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