Retentive force of experimental nickel-free cup-yoke-type dental magnetic attachments

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Abstract

Closed magnetic circuit dental magnetic attachments typically use non-magnetic stainless steel containing nickel as shield rings or spacers to form the magnetic circuit. However, nickel can cause metal allergies, prompting the demand for nickel-free products. This study aimed to develop an experimental nickel-free magnetic attachment and evaluate its retentive force. Chromium, an antiferromagnetic material that is not magnetically attracted to magnets, was plated onto the disk yoke to serve as the shield ring. The disk yoke and cup yoke were laser-welded together, including the chromium plating, to fabricate the experimental magnetic attachment. Retentive force was measured according to ISO 13017 test procedures, including tests with the keeper laterally displaced. Hardness across the mating surface, from edge to center, was also measured. Results were compared to those of a same-sized commercial magnetic attachment, the Physio Magnet 4813. The experimental attachment demonstrated equivalent retentive force to the conventional product. Its behavior during lateral displacement was also similar. The hardness values indicated that the chromium concentration in the shield ring was higher than that of conventional products, suggesting superior corrosion resistance. Thick chromium plating was confirmed to function effectively as a shield ring, enabling the successful development of a nickel-free dental magnetic attachment.

Introduction

Japanese dental magnetic attachments adopt a closed magnetic circuit design. As a result, they exhibit high retentive force even in a compact size compared to open magnetic circuit attachments (i.e., general permanent magnets) [1]. To form a closed magnetic circuit, the magnetic assembly consists of both magnetic and non-magnetic stainless steels. The magnetic stainless steel serves as a yoke to facilitate the smooth flow of magnetic flux, while the non-magnetic stainless steel is used for shielding rings (cup-yoke type) or spacers (sandwich type) to magnetically insulate the flux[1]. Austenitic stainless steel, such as SUS 316L (Fe-18%Cr-12%Ni-2%Mo), which contains a small amount of nickel, is typically used as the non-magnetic stainless steel[1,2]. SUS 316L, also known as surgical stainless steel, has high biocompatibility and is widely used in medical implants. To date, there have been no reported cases of metal allergies caused by dental magnetic attachments. However, nickel is classified as a harmful element according to ISO standard and JIS[3,4], highlighting the demand for developing magnetic assemblies that do not contain nickel. Some overseas dental magnetic attachments employ a simple open magnetic circuit structure, where permanent magnets are merely covered with stainless steel or titanium[5,6]. These products are nickel-free and may appear to be safer and more advantageous at first glance. However, open magnetic circuits suffer from significant magnetic field leakage and exhibit lower retentive force relative to their size[1,5,6]. To address concerns about Japanese dental magnetic attachments while maintaining their superior performance, we have been working on the development of a nickel-free, closed magnetic circuit dental attachment.

In cup-yoke-type magnetic attachments, non-magnetic stainless steel is used as a shielding ring to block magnetic flux. In our previous research, we explored the use of nitrogen-stabilized austenite phase (γ-phase), which forms when nitrogen is dissolved into the ferrite phase (α-phase) of magnetic stainless steel, as a magnetic shielding material[7]. As a result, it was found that by performing heat treatment to dissolve nitrogen into the disk yoke as a solid solution, a shielding ring integrated with the disk yoke could be formed. This method had advantages such as the ability to control the thickness of the γ-phase by adjusting the heat treatment time and the elimination of the need for the cladding process in the manufacturing of the shield disk, which consists of the disk yoke and the shield ring. A prototype was subsequently fabricated, and its retentive force was found to be comparable to that of conventional products[8]. However, due to poor yield caused by insufficient corrosion resistance, commercialization of this method was ultimately postponed.

Therefore, we considered using titanium or gold, both of which are metal elements traditionally utilized in dentistry, as magnetic shielding materials and evaluated their laser weldability with the magnetic stainless steel used for the yoke[9,10]. The results revealed that titanium readily forms intermetallic compounds when alloyed with iron, leading to brittle weld beads and poor practicality. On the other hand, gold demonstrated strong weldability with stainless steel, making it a promising candidate. However, gold is an expensive material, and its recovery during cutting and polishing is challenging, resulting in high costs that pose a significant barrier to commercialization.

As a new magnetic shielding material, we focused on chromium, which exhibits antiferromagnetic properties. According to the equilibrium phase diagram of Fe-Cr system[11)], although the brittle σ-phase may form under certain conditions, iron and chromium are largely mutually soluble in all proportions. Since chromium is already a component of magnetic stainless steel, it appears to be a compatible material.

Objective

In this study, we applied chromium plating technology to fabricate a nickel-free magnetic assembly and evaluated its retentive force characteristics.

Materials and Methods

1. Dental magnetic attachment

This study focuses on a circular cup-yoke-type magnetic attachment. A thick layer of chromium was electroplated onto the disk yoke to serve as a shielding ring. The disk yoke was then incorporated into the magnetic assembly and laser-welded to the cup yoke. The mating face was polished and magnetized in the same manner as commercial products, and a nickel-free magnetic assembly (φ4.8 × 1.3 mm) was fabricated. The prototype magnetic assembly was paired with a commercially available keeper of the same diameter (φ4.8 × 0.8 mm) for experimentation. Additionally, a commercially available magnetic attachment of the same size (Physiomagnet 4813, Morita) was used as a comparison.

2. Retentive force measurement

A digital force gauge (ZPS, Imada) was connected to a retentive force measurement device compliant with ISO 13017:2020[3)]. Following the test method outlined in ISO 13017, the crosshead speed was set to 2 mm/min, and the retentive force of each magnetic attachment combination was recorded at a sampling rate of 1 kHz ($n = 5$). Applying the known time and speed values, distance was calculated then a retentive force curve generated. Retentive force was measured both when the mating faces were in precise contact and when the keeper was laterally displaced from the precisely contacted position. The measurement was repeated at 100 μm intervals until the keeper detached from the magnetic assembly.

3. Hardness test

A micro-Vickers hardness tester (HM–221, Mitutoyo) was used under a load of 1.961 N (200 gf) with a dwell time of 15 s ($n = 3$). Hardness was measured at 100 μm intervals from the edge to the center of the mating surface of the magnetic assembly. The hardness of the keeper's mating surface was also measured.

4. EDS analysis of chromium concentration in the welded region

The welded region on the mating face of the prototype was observed using an SEM equipped with EDS (SU5000 + EDAX Pegasus EDS/EBSP, Hitachi High-Tech Corp.). The chromium concentration in the welded region was semi-quantitatively analyzed by line analysis.

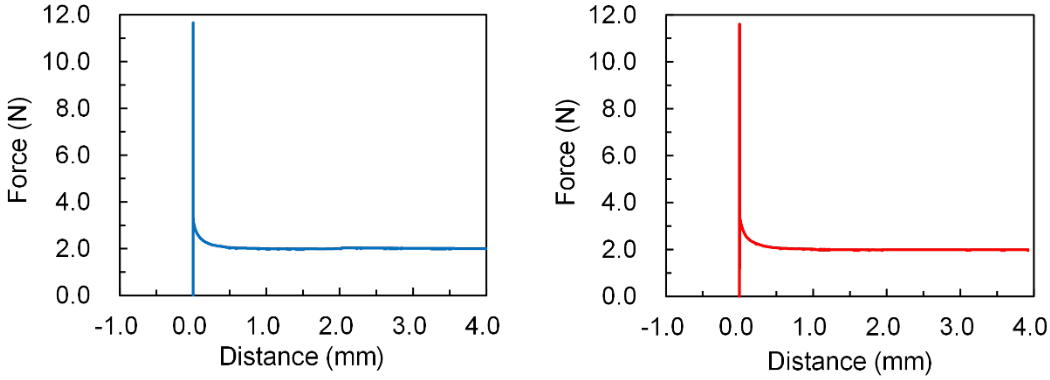
5. Statistical analysis

Statistical analysis was performed using ANOVA and Tukey's HSD test ($\alpha = 0.05$) to determine significant differences.

Results

1. Retentive force

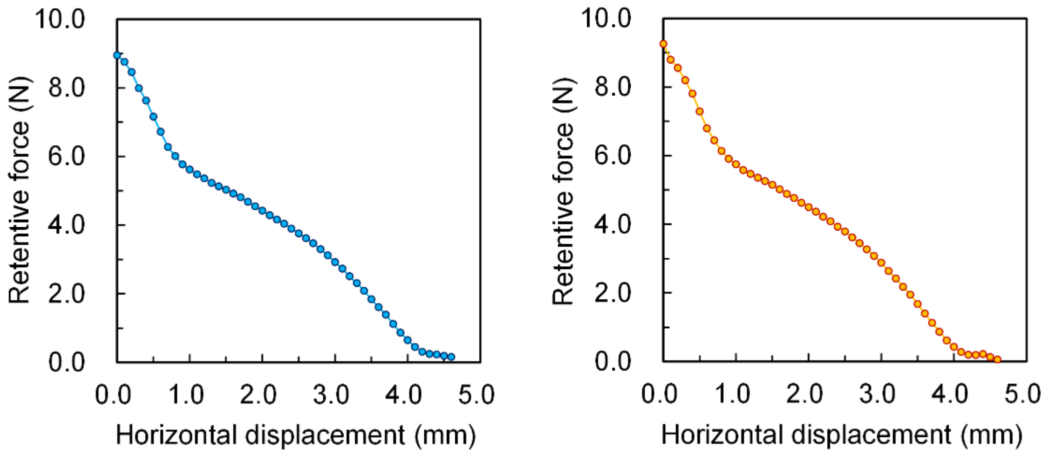
The average retentive force of the prototype magnetic attachment was 9.13 N (±0.31 N), and no significant difference was observed compared to the conventional product ($p > 0.05$). Additionally, the maximum retentive force for both was the same at 9.67 N. An example of the retentive force curves for these magnetic attachments is shown in Fig. 1. The point where the mating faces separated was defined as 0 mm. The retentive force curves for both the prototype and the conventional product were similar, with a rapid decrease in retentive force observed as the mating faces separated.



(a) (b)

Fig. 1 Retentive force curve. (a) protype, (b) conventional product

Retentive forces at lateral displacement of the keeper are shown in Fig. 2. As the lateral displacement increased, the retentive force gradually decreased, exhibiting several inflection points. When the displacement was small, the retentive force dropped sharply, and once the displacement exceeded 1 mm, the decrease became more gradual with a convex shape. When the displacement exceeded 4 mm, the decrease continued more gently with a concave shape. This behavior was observed for both types of magnetic attachments.



(a) (b)

Fig.2 Retentive force against horizontal displacement (a) protype, (b) conventional product

2. Hardness

Figure 3 presents representative hardness test results for the mating surfaces of magnetic assemblies. The diameter of the mating face is 4.8 mm, so the center of the mating face is at 2.4 mm from the edge. The hardness of the yoke area in the prototype was 220–230 HV, which was similar to that of the conventional product ($p > 0.05$). Additionally, the hardness of the keeper was 247.6 (±4.8) HV, which was higher than that of the yoke ($p < 0.05$). For both magnetic assemblies, the hardness was significantly higher ($p < 0.05$) in a range of about 400 μm, between 0.3 mm and less than 0.8 mm from the edge, compared to the yoke area. The prototype had a hardness of approximately 400 HV, while the conventional product had approximately 350 HV.

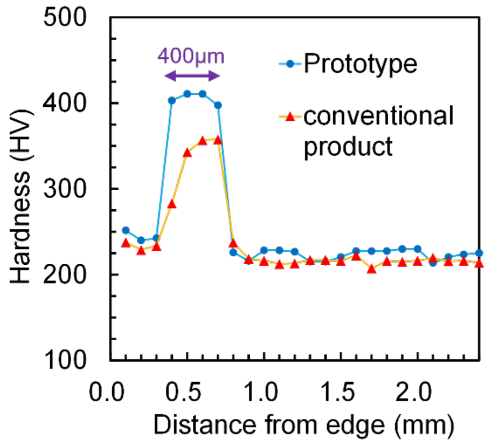


Fig. 3 Hardness profile of the mating face of magnetic assembly

A photograph of the prototype magnetic assembly's mating surface with the hardness profile results is shown in Fig. 4. By adjusting the angle of light when taking the photograph, the welded shielding ring and yoke parts can be clearly identified by the naked eye, as shown in this figure. As indicated in the figure, the areas with increased hardness corresponded to the welded sections.

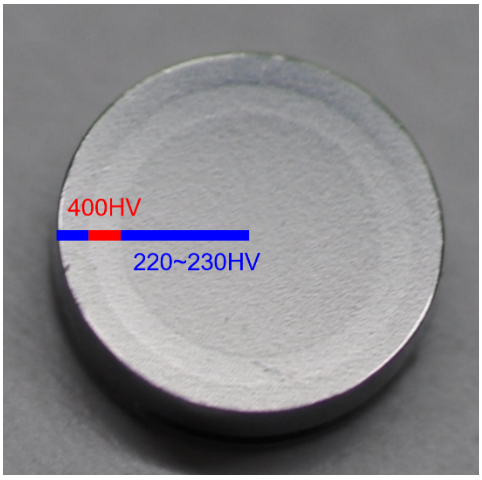


Fig. 4 Mating face view of magnetic assembly and its hardness

3. Chromium concentration in the welded region

The chromium concentration in the welded region of the prototype ranged from 55% to 60%. No precipitates or extreme concentration variations were observed in the welded region.

Discussion

1. Retentive force characteristics of the prototype nickel-free magnetic attachment

The retentive force of the prototype magnetic attachment was comparable to that of the conventional product of the same size in terms of both average and maximum values. According to ISO standard and JIS[3,4)], to avoid misleading representations, the measured retentive force must be at least 85% of the value stated in the product documentation. The catalog-listed retentive force for the conventional product is 9.6 N. Since 85% of this value is 8.16 N, the measured values of the prototype sufficiently exceed this threshold. Therefore, when marketing this prototype as a dental magnetic attachment, it would be permissible to indicate a retentive force of 9.6 N. The retentive force curves of these magnetic attachments were also identical, and the force rapidly decreased upon detachment of the mating faces. This behavior is characteristic of closed magnetic circuit attachments and indicates minimal magnetic field leakage. In contrast, open magnetic circuit attachments exhibit greater magnetic field leakage, allowing the magnetic force to extend farther, resulting in a more gradual decrease in retentive force after the mating faces separate.

The behavior of retentive force when the keeper was laterally displaced was also the same for both the prototype and the conventional product. Fundamentally, lateral displacement reduces the contact area of the mating face, leading to a decrease in retentive force. In the case of a cup-yoke-type structure, this behavior is accompanied by changes in the contact area related to the closed magnetic circuit, where the cup yoke's contact area with the keeper is primary and the disk yoke's contact area is secondary[12)]. In other words, the identical behavior of retentive force during lateral displacement indicates that the magnetic circuit functions equivalently in both magnetic attachments of the cup-yoke type.

These results demonstrate that the prototype nickel-free magnetic attachment possesses the same retentive force characteristics as the conventional product. The cup-yoke, disk-yoke, and permanent magnet components are identical to those used in the conventional product. The key difference is that the conventional product employs SUS 316L for the shielding ring, whereas the prototype utilizes chromium. The thick chromium layer, applied through electroplating, functioned effectively as a shielding ring, and its retentive force characteristics were confirmed to be equivalent to those of the conventional product.

In conventional manufacturing of magnetic assemblies, a cladding process is required to bond non-magnetic stainless steel to magnetic stainless steel. This study has demonstrated that applying thick electroplating can serve as an alternative to this process. The thickness of the plated layer can be controlled through current and time adjustments, allowing for either thinning or thickening of the shielding ring. Adjusting the thickness of the shielding ring could potentially contribute to optimizing the magnetic circuit.

2. Characteristics of the shielding ring using chromium plating

The hardness of the yoke in the prototype was the same as that in the conventional product. As mentioned earlier, this is because the prototype's yoke was made from the same material as the conventional product. The keeper was slightly harder than the yoke. Both the yoke and keeper were made from SUS XM27-equivalent material (Fe-26%Cr-1%Mo), a magnetic alloy. According to JIS[2)], the hardness of SUS XM27 in the annealed state is specified as 200 HV or lower. The slightly higher measured hardness is presumed to result from work hardening due to polishing and barrel processing. If there were a significant difference in hardness between the yoke and the keeper, the softer material would experience excessive wear during use. The moderate difference observed in this study is considered desirable.

In both magnetic assemblies, the hardness of the welded shield ring area was greater than that of the yoke. The hardened area was approximately 400 μm wide, corresponding to the weld width. While JIS defines the hardness of hard chromium plating as 750 HV or higher[13)], creating the impression that it is extremely hard, the hardness of metallurgically produced metallic chromium typically ranges from 200 to 350 HV[14)]. On the other hand, the welded region in this study was not pure chromium, but rather an Fe-Cr alloy formed by the alloying of the plated chromium and the iron from the yoke. The chromium concentration in the welded region was 55–60%, and its hardness value (approximately 400 HV) was generally consistent with the hardness of binary Fe-Cr alloys with the same concentration reported in previous studies[15)]. Chromium is well known for enhancing the corrosion resistance of iron through passivation, as seen in stainless steel. The higher chromium concentration in the shield ring of the prototype compared to the SUS 316L (Fe-18%Cr-12%Ni-2%Mo) used in the conventional product suggests that the prototype may exhibit superior corrosion resistance.

Conclusion

A thick chromium plating functioned effectively as a shield ring. The retentive force characteristics of the prototype were equivalent to those of the conventional product. The development of a nickel-free dental magnetic attachment was successfully achieved.

References

1. Y. Tanaka, New dental magnetic attachment, pp 26-57, Ishiyaku Publishers, Inc, Tokyo, 2016.
2. ISO 16143-2:2014. Stainless steels for general purposes－Part 2: Corrosion-resistant semi-finished products, bars, rods and sections.
3. ISO 13017:2020. Dentistry—Magnetic attachments.
4. JIS T6543:2017. Dentistry—Magnetic attachments.
5. Y. Takada, M. Takahashi, Y. Kinouchi, Y. Nakamura, Y. Tanaka, H. Sato, A. Izumida and T. Tenkumo: Materials and internal structures of foreign-made dental magnetic attachments, J J Mag Dent, 22(1), 96-102, 2013.

6. J. Tanaka, H. Mizutani, Y. Furuichi, K. Sasaya, H. Wakai, T. Mizuguchi, S. Sakuma and K. Hoshino: Comparison of the basic performance of magnetic attachments fabricated within and outside of Japan, J Jpn Soc Oral Implant, 31(1), 56-63, 2018.
7. Y. Takada, H. Yamaguchi, H. Sakatsume, K. Sato, K. Sasazaki, A. Kikuchi and M. Takahashi: Development of a magnetic shielding ring that consists of solid-solution containing nitrogen in stainless steel to take the first step toward nickel-free magnetic attachments, J J Mag Dent, 24(1), 62-67, 2015.
8. Y. Takada, M. Takahashi, G. Togawa, H. Sakatsume: Development of closed magnetic circuit attachment using nitrogen solid-solution in stainless steel, Proceedings of the 31st Annual Conference of the Japanese Society of Magnetic Applications in Dentistry, P331-N, 2021.
9. Y. Takada, J. Shiroto, M. Kikuchi and M. Takahashi: Weldability between the nickel-free shield-ring materials and the magnetic stainless steels by laser beam, J J Dent Mater 30(5), 325, 2011.
10. Y. Takada, M. Takahashi, A. Kikuchi, H. Sato, A. Izumida, Y. Nakamura, Y. Tanaka, and T. Tenkumo: Laser welding between titanium as a magnetic shielding material and SUS 447J1 stainless steel, J J Mag Dent, 22(1), 90-95, 2013.
11. ASM International Alloy Phase Diagram and Handbook Committee. ASM Handbook Vol. 3 Alloy Phase Diagrams: Section 2, Binary Aloy Phase Diagrams. Materials Park: ASM Int; 1992, 152.
12. M. Takahashi, H. Sakatsume, M. Kanyi and Y. Takada: Effect of horizontally shifting the center of the magnetic assembly and that of the keeper on the retentive force of cup-yoke dental magnetic attachments, J J Mag Dent, 26(2), 8-14, 2017.
13. JIS H8615:1999. Electroplated coatings of chromium for engineering purposes.
14. OTEC.Co.,LTD. Plating information, Hard chrome plating. <https://www.otec-kk.co.jp/hard-chrome-plating/plating-information/> [accessed 25.0130]
15. N. Matsui, K. Matsui, K. Kobayashi, A. Sugiyama and K. Ozaki: Effects of Cr content on mechanical properties of Fe-Cr alloy, J Jpn Soc Powder Powder Metallurgy, 46(11), 1179-1184, 1999.