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Relation between Attractive Force and Keeper Surface Characteristics of Iron-neodymium-boron Magnetic Attachment Systems

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The purpose of this study was to evaluate the influence of heating, cast bonding, and subsequent polishing procedures on attractive force of magnetic attachments. Two magnetic attachment systems with keepers of different chemical compositions (Hicorexslim 3013, 447J1; Magfit EX400, AUM20) were employed. Keepers examined were: (1) untreated; (2) heated; (3) cast-bonded with Ag-Pd alloy; (4) cast-bonded with Ag-Pd alloy and polished; (5) cast-bonded with gold alloy; and (6) cast-bonded with gold alloy and polished. Attractive force was determined with a force gauge, and surface structure was evaluated with scanning laser and electron microscopes. Attractive force of the Hicorex system was reduced by cast bonding, whereas that of the Magfit system was reduced by both heating and cast bonding. However, attractive force of both systems was somewhat recovered through the polishing process. Based on the findings of this study, it was suggested that careful polishing after cast bonding was indispensable to the recovery of attractive force for both attachment systems.

Keywords: Attachment, Keeper, Magnet

INTRODUCTION

A number of magnetic attachment systems have been developed and applied to patients for retaining prostheses and removable dentures[1-12]. A keeper component of magnetic attachments is usually cast-bonded, soldered, or cemented[2] to root caps, restorations, and denture frameworks, whereas the magnetic assembly is mechanically retained or adhesively bonded[13,14] to the denture base material with resin-based materials.

It is desirable for magnetic attachments to maintain original attractive force as long as possible. One chief cause for reduction in attractive force is the corrosion of magnetic alloys. However, this problem has been overcome considerably by embedding magnetic alloys in cup and disk yokes made of corrosion-resistant stainless steel[2].

Another problem associated with reduction of attractive force is degradation and deformation of keepers. It has been found that application of high temperature greater than 650℃ negatively affected the corrosion resistance of SUS 447J1 stainless steel[15]. Furthermore deformation of keeper surfaces was detected after routine dental laboratory procedures, including cast bonding[16]. Prior to the cast bonding procedure, a keeper plate surrounded by wax is invested into a mold material. The wax is then burned out and replaced by casting alloy. As a result, the keeper is embedded in the casting alloy and mechanically retained, *i.e.*, cast-bonded. It is thus thought that shrinkage after cast bonding of the alloy induces deformation of the keeper surface.

Iron-neodymium-boron magnets have been applied to several dental magnetic systems due to their improved attractive force[3,5,17]. Although varying properties have been reported about magnetic systems, little information is available about the relation between attractive force and surface condition of the keeper component. Therefore, the two-fold aims of the current study were to evaluate: (1) the attractive force of two magnetic systems; and (2) change of surface characteristics of the keepers during routine laboratory procedures, especially in relation to the cast bonding procedure.

MATERIALS AND METHODS

Materials

Two iron-neodymium-boron ($Fe_{14}Nd_2B$) magnetic attachment systems were assessed in this study. One system consisted of a cup-yoke type magnetic assembly (Hicorexslim 3013, Hitachi Metals Ltd., Osaka, Japan) and a cylindrical keeper made of SUS 447J1 steel (abbreviated as 447J1). The other system comprised a sandwich-yoke type magnetic assembly (Magfit EX400W, Aichi Steel Co. Ltd., Tokai, Japan) combined with a round-end rectangular parallelepiped keeper made of AUM20 steel. A silver-palladium-copper-gold alloy (abbreviated as Ag-Pd) and a type

Table 1 Materials assessed

Material/Trade name	Manufacturer	Lot number	Composition (mass%)	Dimensions (mm)
Magnetic Assembly				
Hicorexslim 3013	Hitachi Metals Ltd., Osaka, Japan	021004		Ø3.0×1.3
Magnet			$Fe_{14}Nd_2B$	
Cup and disk yoke			SUS 447J1*	
Non-ferromagnetic ring			SUS 316L (65 Fe, 17 Cr, 13 Ni)	
Magfit EX400W	Aichi Steel Corp., Tokai, Japan	991217C		3.4×2.4×1.5
Magnet			$Fe_{14}Nd_2B$	
Yoke			AUM20**	
Non-ferromagnetic case			SUS 316L (68 Fe, 16 Cr, 12 Ni)	
Keeper				
Hicorexslim 3013	Hitachi Metals Ltd., Osaka, Japan	000123	SUS 447J1*	Ø3.0×0.8
Magfit EX400	Aichi Steel Corp., Tokai, Japan	22039J, 990609D	AUM20**	3.4×2.4×0.8
Casting Alloy				
Pallatop 12 Multi	Dentsply-Sankin, Tokyo, Japan	C640764	12 Au,20 Pd,50 Ag,15 Cu	
Casting Gold Type III	Ishifuku Metal Industry Co. Ltd., Tokyo, Japan	1405143, 1310300	74 Au, 10 Ag, 3 Pt, 2 Pd, 9.9 Cu	

*SUS 447J1: 67.59 Fe, 30.0 Cr, 2.0 Mo, 0.18 Ni, 0.15 Si, 0.04 Mn, 0.015 S, 0.015 P, 0.007 N, 0.003 C (mass%)
**AUM20: 79 Fe, 19 Cr, others (mass%)

3 gold alloy were used as coping materials. Information on the materials is summarized in Table 1.

Preparation of cast-bonded keeper specimens

Coronal part of an artificial maxillary lateral incisor (Shofu Inc., Kyoto, Japan) was cut, and a root surface with a cylindrical cavity was prepared using a rotary cutting instrument (Fig. 1). Wax patterns of both the Hicorex and Magfit keepers (Fig. 2) were prepared, sprued with a plastic rod (S-2-5, Ishifuku Metal Industry Co. Ltd., Tokyo, Japan), and invested into a cristobalite mold material (Cristobalite, GC Corp., Tokyo, Japan). One hour after investing, the mold was heated in an electric oven (KDF-008S, Denken Co., Ltd., Kyoto, Japan) at a heating rate of 8°C/minute below 200°C, 15°C/minutes from 200 to 400°C, and then from 400°C to 700°C. The mold was held at 200°C for 20 minutes, at 400°C for 20 minutes, and at 700°C for 30 minutes to burn out the wax and plastic pattern material. Following which, either the Ag-Pd or gold alloy was cast in the mold with a centrifugal casting apparatus.

The castings were cooled to room temperature and ultrasonically washed with water (SUC-110, Shofu Inc.). Cast specimens were cleaned with a steam cleaner with compressed air and hot water (Steam Cleaner-Z SSC-VI, Shofu Inc.). Five specimens were prepared for each combination of keepers and alloys. Attractive force of the cast-bonded keepers was determined at as-cast state.

Thereafter, the specimens were ground with a series of abrasive papers up to #2,000 (Tri-M-ite, Sumitomo 3M Ltd., Tokyo, Japan). Next, the ground surfaces were polished with a cutting disk (Microcut disk, UF1,200, #4,000, Buehler Ltd., Lake Bluff, IL, USA) under a continuous 1.0 N loading which was applied for 30 seconds (Digital table scale 1458H, Tanita Co. Ltd., Tokyo, Japan). Attractive force of the polished keepers was then determined.

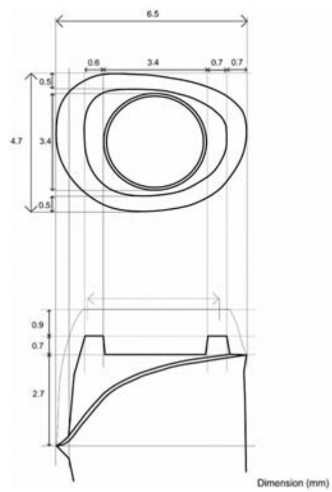

Fig. 1 Abutment preparation for a root cap with a cast-bonded keeper. Arrow above the distal view of abutment indicates the area to seat the keeper.

Preparation of heated keepers and experimental controls

Five Hicorex keepers and five Magfit keepers without

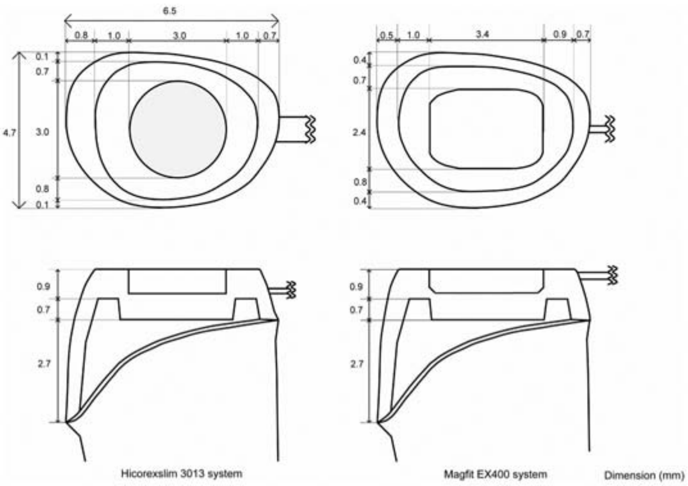

Fig. 2 Dimensions of cast-bonded specimens with the keepers.

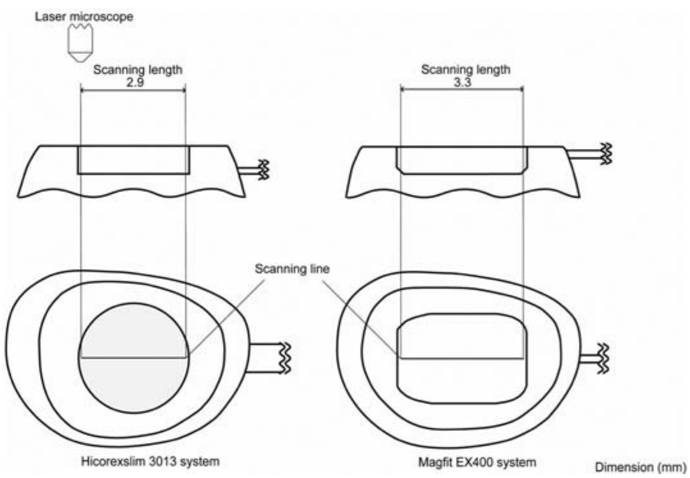

Fig. 3 Location and length of scanning for evaluation of surface characteristics of the keepers. The line between the start and end points including the center of the keeper was defined as the baseline.

wax pattern were invested into the cristobalite material, and heated to 700℃ as described above. The invested keepers were treated with the same procedure as the cast-bonded specimens. These specimens were then considered as the 'merely heated' specimens. Additional five Hicorex keepers and five Magfit keepers as received from the manufacturers were used as untreated experimental controls.

Determination of attractive force

A magnetic assembly was placed on each of the six differently treated keepers (cast-bonded with Ag-Pd alloy, polished after cast bonding with Ag-Pd alloy, cast-bonded with gold alloy, polished after cast bonding with gold alloy, heated, and as-received control), and they were separately fixed in a jig with a self-curing acrylic resin. Direction of loading was perpendicularly aligned to the keeper surface using a split level. Attractive force (N) was determined with a digital force gauge (FGC-1, Nidec-Shimpo Corp., Kyoto, Japan). Average, median, and standard deviation of five replications were calculated for combinations of two magnetic systems and six keeper conditions.

Evaluation of surface characteristics of keepers

Surface texture of the keepers was analyzed by means of a scanning laser microscope (1LM21W, Lasertec, Yokohama, Japan). Two baseline points were set at the periphery of each keeper. Scanning length through the center of the keeper was 2.9 mm for the Hicorexslim 3013 system and 3.3 mm for the Magfit EX400 system (Fig. 3). Maximal (convex) or minimal (concave) height in μm from the baseline of the keeper surface was recorded. Average, median, and standard deviation of five replications were calculated for six keeper surface conditions of two magnetic systems.

Selected specimens after surface preparation were sputter-coated with osmium and observed with a scanning electron microscope (SEM; S4300, Hitachi High-Technologies, Tokyo, Japan) operated at 15 kV.

Statistical analysis

As shown in Table 1 and Fig. 3, structural concept of the magnetic assembly, as well as outline shape and scanning length of the keepers, differed considerably between the two magnetic systems. Statistical analysis, therefore, was not performed on the differences between the Hicorex and Magfit systems. Results of attractive force and surface analysis for each of the two systems were primarily analyzed by Levene's test for evaluation of equality of variances. When results of the Levene's test did not show homoscedasticity in at least one category, Dunnett's T3 multiple comparisons were further performed with the value of statistical significance set at p=0.05. The relation between attractive force and maximal/minimal height from the baseline for each magnetic system, except for polishing state, was analyzed with Pearson's correlation.

RESULTS

Attractive force

Levene's test run on the attractive force of Hicorexslim 3013 and Magfit EX400 systems revealed that the results of both systems did not show homoscedasticity. Hence, the results were compared

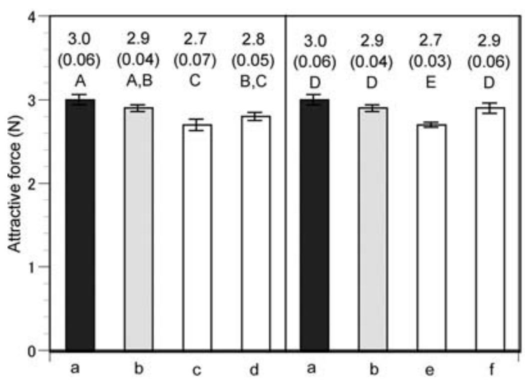

Fig. 4 Attractive force of the Hicorexslim 3013 system: (a) as received (Control); (b) heated; (c) cast-bonded with Ag-Pd alloy; (d) polished after cast bonding with Ag-Pd alloy; (e) cast-bonded with gold alloy; and (f) polished after cast bonding with gold alloy. Identical capital letters indicate that attractive forces are not statistically different (p>0.05).

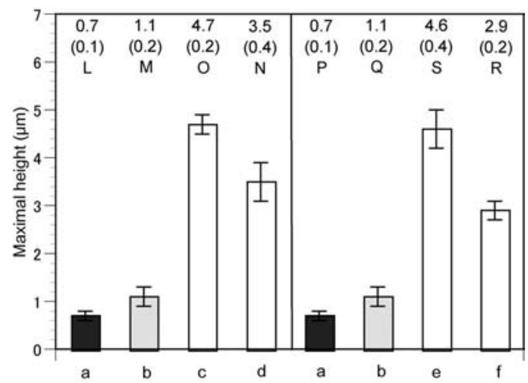

Fig. 6 Maximal height from baseline of Hicorexslim 3013 keeper: (a) as received (Control); (b) heated; (c) cast-bonded with Ag-Pd alloy; (d) polished after cast bonding with Ag-Pd alloy; (e) cast-bonded with gold alloy; and (f) polished after cast bonding with gold alloy. Identical capital letters indicate that maximum height values are not statistically different (p>0.05).

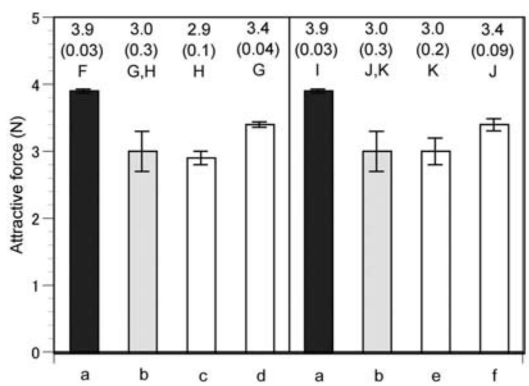

Fig. 5 Attractive force of the Magfit EX400 system: (a) as received (Control); (b) heated; (c) cast-bonded with Ag-Pd alloy; (d) polished after cast bonding with Ag-Pd alloy; (e) cast-bonded with gold alloy; and (f) polished after cast bonding with gold alloy. Identical capital letters indicate that attractive forces are not statistically different (p>0.05).

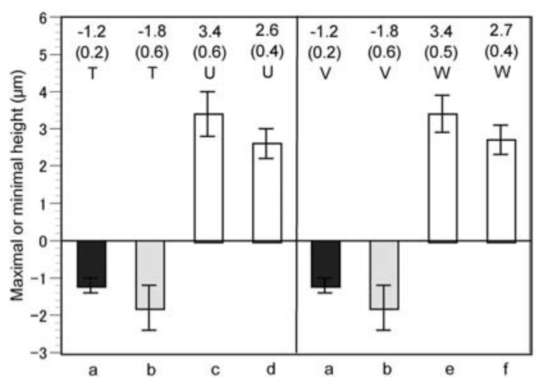

Fig. 7 Maximal or minimal height from baseline of Magfit EX400 keeper: (a) as received (Control); (b) heated; (c) cast-bonded with Ag-Pd alloy; (d) polished after cast bonding with Ag-Pd alloy; (e) cast-bonded with gold alloy; and (f) polished after cast bonding with gold alloy. Identical capital letters indicate that maximal/minimal height values are not statistically different (p>0.05).

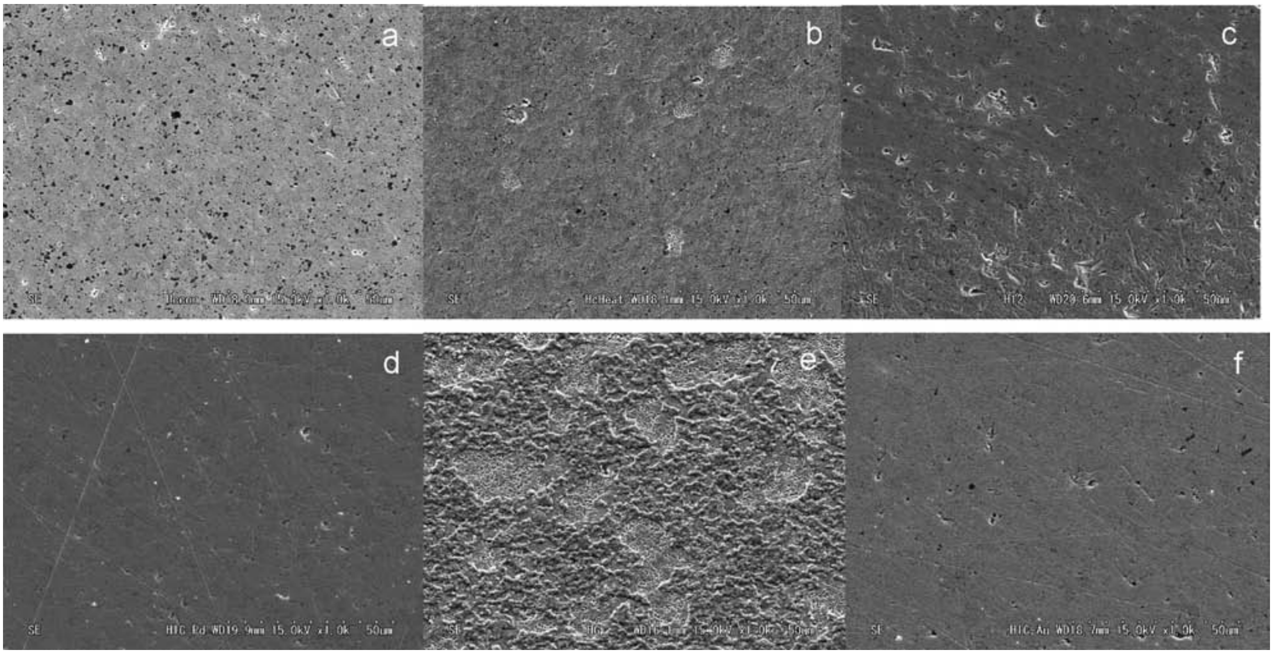

Fig. 8 Scanning electron micrographs of Hicorexslim 3013 keepers: (a) as received (Control); (b) heated; (c) cast-bonded with Ag-Pd alloy; (d) polished after cast bonding with Ag-Pd alloy; (e) cast-bonded with gold alloy; and (f) polished after cast bonding with gold alloy.

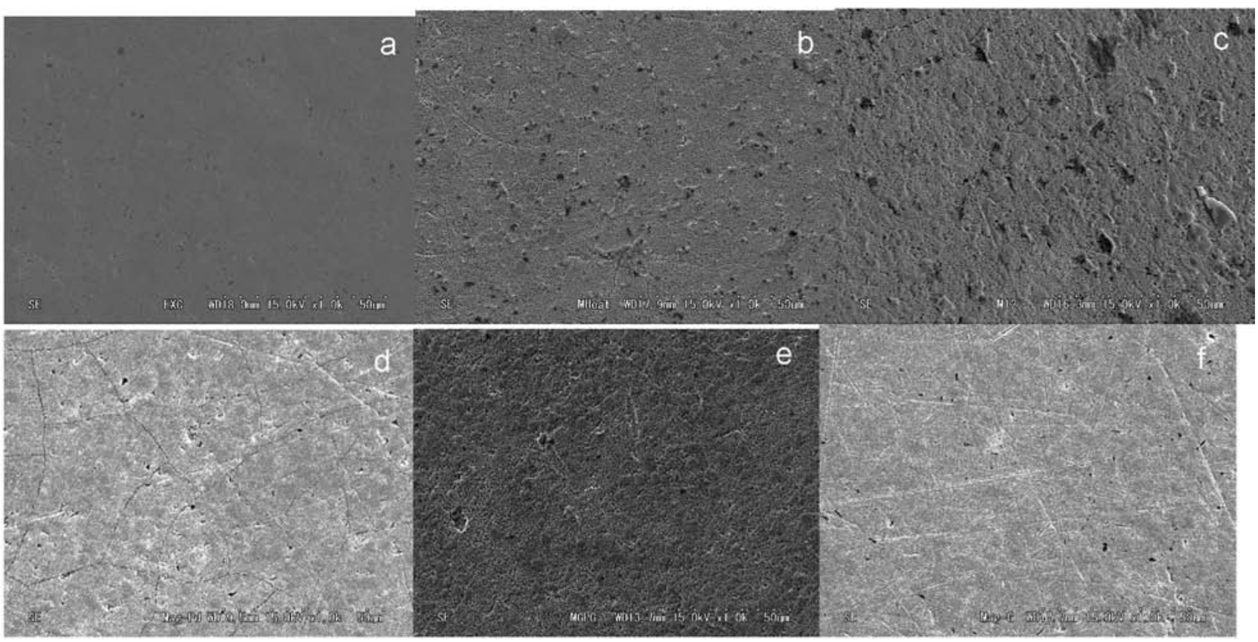

Fig. 9 Scanning electron micrographs of Magfit EX400 keepers: (a) as received (Control); (b) heated; (c) cast-bonded with Ag-Pd alloy; (d) polished after cast bonding with Ag-Pd alloy; (e) cast-bonded with gold alloy; and (f) polished after cast bonding with gold alloy.

with Dunnett's T3 test. Attractive force of the Hicorex system is summarized in Fig. 4. The original attractive force of the Hicorexslim 3013 system was 3.0 N, and the value was not negatively affected by the heating of keeper component (2.9 N, categories A and D). Attractive force of cast-bonded groups, however, was 2.7 N (categories C and E) and the value was significantly lower than the control or heated group. However, attractive force was recovered by subsequent polishing (2.8 N, categories B and C; 2.9 N, category D).

Figure 5 shows the results for the Magfit system. The original attractive force of Magfit EX400 was 3.9 N (categories F and I), and the value was significantly reduced by application of heat to the keeper component (3.0 N, categories G, H, J, and K). Cast-bonded specimens also resulted in 2.9 and 3.0 N attractive forces, and they were significantly lower than the value of the control (categories H and K). Unlike the Hicorex system, differences among the heated group and the two cast-bonded groups were not significant (categories H and K, $p>0.05$). Attractive force of the Magfit keepers recovered to the 'merely heated' level when the surface was polished after the cast bonding process (3.4 N, categories G and J).

Maximal/Minimal height

Height from the baseline (μm) of the keepers was also compared with Dunnett's T3 test. Figure 6 summarizes the maximal height measurements from the baseline for Hicorexslim 3013 keeper. Maximal height was 0.7 μm for the untreated control group (category L), and the value was changed statistically by the heating of keeper component (1.1 μm, category M). Maximal height of cast-bonded groups was 4.7 μm with Ag-Pd alloy and 4.6 μm with gold alloy. Although these two values were not statistically different from each other, they were significantly greater than the value of the control specimen. After polishing, the maximal height value was reduced.

Figure 7 shows the results for the Magfit system. The original surface texture of Magfit EX400 keeper was somewhat concave, hence the height was expressed as minimal height (−1.2 μm, categories T and V) rather than as maximal height. This value was not statistically influenced by the heating of keeper component (−1.8 μm, categories T and V). The surface of Magfit keeper changed from concave to convex structure by cast-bonding the keeper component. Maximal height after cast bonding was 3.4 μm for both alloys (categories U and W), and the value was statistically different from that of the control. As for the polishing procedure after cast bonding, it did not change the maximal height values of the cast-bonded Magfit keepers with both alloys (categories U and W).

Pearson's product moment correlation coefficient between attractive force and maximal/minimal height from the baseline was $r=-0.907$ ($p<0.001$) for the Hicorex system and $r=-0.530$ ($p=0.016$) for the Magfit system.

Surface texture

Figures 8 and 9 show the change of surface texture of the Hicorex and Magfit keepers, respectively. Both keepers showed a roughened appearance after heating. In addition, roughened surfaces were apparent for both keepers after they were cast-bonded with gold alloy. However, surface smoothness was considerably recovered through the polishing procedure.

DISCUSSION

In this study, two iron-neodymium-boron magnetic attachment systems with different yoke and keeper compositions were assessed. With the Hicorex system, the keeper was made of 447J1 with 30% chromium. With the Magfit system, the keeper was made of AUM20 which contained 19% chromium.

Attractive force of the Hicorex system was not negatively affected when the keeper was heated in the investment material. On the effect of heat history, Takada and Okuno[15] reported that either FeCr or $Fe_{18}Cr_6Mo_5$ was formed on the 447J1 steel surface after subjecting to heating at 650−750℃ for two hours or more. In light of this finding, they recommended that the heat time applied to casting molds should be kept under one hour. Heating period of the Hicorex system above 400℃ was approximately 50 minutes in the current experiment. This heating time was within the recommended duration of Takada and Okuno[15], and the result obtained further supported the resistance of Hicorex 447J1 keeper to heat during the cast bonding procedure. Indeed, the keeper surface after heating (Fig. 8b) was smoother than that of Magfit (Fig. 9b). These micrographs evidently showed that the two keepers were substantially different in stability in a high temperature environment.

Of the two systems, the attractive force of Magfit system was significantly reduced when the keeper was heated in the investment material. This difference in attractive force between the two magnetic systems to heat treatment could be attributed to the chromium content. Generally, a steel alloy with high chromium content is more corrosion-resistant than the alloy with low chromium content. Against this background, it was speculated that the formation of precipitate, such as FeCr[15,18], on the heated AUM20 steel surface negatively affected the attractive force of Magfit system. Nonetheless, this proffer requires further clarification as spectroscopic analysis was not performed in the current study. Moreover, it should also be highlighted that increased surface roughness after heating (Figs. 9a, b) might negatively affect the attractive force of Magfit keeper.

Maximal or minimal height from the baseline of the keeper surface is indicative of the following aspects: integrity of flat surface texture of intact specimens, change of surface texture of the keeper during the laboratory process, and deformation derived thereof. As shown in Figs. 6 and 7, morphological change as a result of heating the keeper was not so remarkable. However, both Hicorex and Magfit keepers demonstrated an increase in convex structure after the cast bonding procedure. At the same time, attractive force was also significantly reduced after cast bonding. These results clearly indicated that cast bonding induced deformation of the keepers. Hence, it could be said that cast bonding is not the best technique for retaining keepers in the coping structure. However, the attractive force of both systems recovered considerably when the keepers were polished with an abrasive system. Based on these results, cast-bonded systems are still therefore one valid and appropriate option in stabilizing keepers in copings or prostheses, if properly polished.

With the Magfit system, the results of Figs. 5 and 7 seemed to suggest that the reduction in attractive force was due to the heating of the keeper component. However, the surface of Magfit keeper changed from a concave to convex structure through the cast bonding process. This result suggested that the actual direct contact area between the keeper and magnetic assembly was less affected through the cast bonding process than in the case of Hicorex system. Indeed, Pearson's product moment correlation coefficient value ($r=-0.530$) soundly supported this hypothesis. As for the Hicorex keeper, cast bonding increased its convexity, but reduced the attractive force. Its high coefficient value of Pearson's product moment correlation ($r=-0.907$) might thus be due to reduction in direct contact area between the magnetic assembly and the keeper, whereby surface convexity was increased through the cast bonding procedure. It should be noted that it is difficult to simulate the change in close contact area between the keeper and the magnetic assembly. Hence, it was speculated that the low coefficient value of Pearson's product moment correlation for Magfit system might be derived from complex changes in surface chemical and morphological structures during cast bonding.

Another factor that could have influenced the attractive force of magnetic attachment systems was the distribution of magnetic flux. As shown in Figs. 4 and 5, reduction in attractive force of the Magfit system was greater than that of the Hicorex system. However, maximal height from the baseline of the Hicorex keeper was greater than that of the Magfit keeper. Air gap between an attachment and a keeper negatively affects the attractive force of magnetic attachments[19]. Thus, the lower reduction in attractive force of the Hicorex system could be that magnetic flux was condensed around the shield material, and that the change of air gap between the shield material and the Hicorex keeper was smaller than that of Magfit.

In conclusion, it was found that cast bonding did affect the flat surface morphology of the keepers. Therefore, clinicians and dental laboratory technicians should keep in mind that adhesive bonding and other techniques may be considered as alternatives to cast bonding for retaining a keeper component in prosthodontic appliances. At the same time, it should also be emphasized that careful polishing after cast bonding was effective for recovering the attractive force of both magnetic attachment systems.

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