INTRODUCTION

In recent years, much progress has been made in adhesion technology for dental materials in dentistry, including the development of a composite resin for operative dentistry and an adhesive resin for prosthodontics. Contraction during polymerization of the resin generates stress in the bond structures with the adherent. This stress leads to failure of the adhesion interface of the adhesive resin and adherent (such as a tooth, metal, or ceramic substrate). Many reports in operative dentistry have studied the stress induced by polymerization shrinkage in composite resins. The stress results in the formation of a gap between the cavity wall and the restorative composite resin, and there is crack formation in the tooth enamel near the cavity wall, a so-called white margin, which may lead to secondary dental caries. However, stresses due to polymerization shrinkage and thermal contraction of a resin are imposed at the adhesion interface and becomes the main factor in fractures. The stress also distorts the metal frame, leading to poor adaptation of maxillary prosthetics and to cracks forming between the crowns of the facing composite resin after curing and trimming to a tooth profile.

These problems are clinically important, but there have been no reports on distortion of a metal frame with an adhesive resin. The studies here were conducted to clarify the relationship between the distortion and the different thicknesses of resin or metal by using three types of specimens, a ring-shaped specimen, a plate-shaped specimen, and a metal frame simulating an anterior arch. The purposes in the present study are to visualize the distortion of the metal frame due to polymerization shrinkage and thermal contraction of the resin and also to discuss the mechanism of the crack formation in the facing composite resin on a long span bridge.

MATERIALS AND METHODS

Materials

Table 1 shows the specimen types, materials, and specimen numbers used for the distortion observations in the present study. Three types of specimens, a ring-shaped specimen, a plate-shaped specimen, and a metal frame simulating an anterior arch, for the distortion observations were made from Au-Ag-Pd-Cu alloy. Distortion due to polymerization shrinkage and thermal contraction of a heat-curing acrylic resin containing 4-META (4-methacryloyloxyethyl trimellitate anhydride, 4-META resin) could be visualized for the ring-shaped specimen, which showed increasing distortion of the metal frame upon adhesion of the resin to the outer metal surface. Distortion of the plate-shaped specimen adhering to 4-META resin decreased with increasing thickness of the cured resin. The distortion of the metal frame simulating an anterior arch of a six-unit bridge with a facing composite resin showed that the curvature of the metal frame was larger after curing of the facing composite resin. However, it recovered most of its original curvature with an associated increase in the number of cracks between the crowns after trimming the resin to a tooth profile.

Keywords: Metal frame, Distortion, Adhesion

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Table 1 Specimens and materials for the distortion observations

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Alloy, Thickness, Surface Modification</th>
<th>Resin, Thickness</th>
<th>Specimen number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring-shaped</td>
<td>Au-Ag-Pd-Cu alloy, 0.3 mm</td>
<td>Acrylic resin containing 4-META (Heat-cured type)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Adloy modification</td>
<td>1.0 mm</td>
<td>—</td>
</tr>
<tr>
<td>Plate-shaped</td>
<td>Au-Ag-Pd-Cu alloy, 0.3 mm</td>
<td>Acrylic resin containing 4-META (Heat-cured type)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Adloy modification</td>
<td>1.0, 2.0, 3.0 mm</td>
<td></td>
</tr>
<tr>
<td>Long span bridge</td>
<td>Au-Ag-Pd-Cu alloy, 0.7, 1.0, 1.2, 1.4, 1.7, 2.1, 2.8 mm</td>
<td>Posterior composite resin (Light-cured with heat-cured type)</td>
<td>12 for 0.7 mm, 1 for other thickness</td>
</tr>
<tr>
<td></td>
<td>Metal primer application</td>
<td>1.5 mm</td>
<td></td>
</tr>
</tbody>
</table>

Observation of distortion of the metal frame

1. Ring-shaped specimen
Figure 1(a) shows the ring-shaped specimen used for visualization of the distortions. The specimen, 20 mm diameter, 10 mm high, and 0.3 mm thick, was made from Au-Ag-Pd-Cu alloy. The ring-shaped metal was formed into a plate by cold working and then made into a ring by soldering. Then the metal ring was annealed at 600°C for 10 min to remove the initial stress from the cold working.

A 1-mm-thick layer of 4-META resin, as shown in Fig.1 (b), was made as follows: Slurry of dental stone was poured into the metal ring and two dowel pins were inserted in the slurry before setting. The ring with the dental stone core was invested in a dental flask with dental stone after attaching 1-mm-thick sheet wax to the outer surface of the ring. After setting the dental stone, the ring with the dental stone core was removed from the dental flask along with the dowel pins and the wax was removed with hot water. Then the outer surface of the metal ring was polished using a buff with aluminum powder slurry (3 μm) and treated with Adloy (for some samples). The ring with the dental stone core was set again into the original position in the dental flask along with the dowel pins. A dough-like 4-META resin was pressed into the 1 mm space and cured under heating conditions of 100°C for 30 min followed by 65°C for 60 min. The ring with the 1-mm-thick layer of resin was removed from the flask after curing. The stone core was also removed from the ring. The ring was cut with a 0.5-mm-thick diamond saw as shown in Fig. 1 (b). The opening after cutting the ring was observed for two different conditions: with and without Adloy modification for adhesion of the resin to the alloy.

2. Plate-shaped specimen
A plate-shaped metal specimen for distortion measurements (40 mm long, 10 mm wide, and 0.3 mm thick) was made by forming Au-Ag-Pd-Cu alloy into a flat plate by cold working and cutting to size. The metal plate was annealed as described above. The outer surface of the metal plate was polished and treated with Adloy for all samples. A layer of dough-like 4-META resin, 1 mm, 2 mm, or 3 mm in thickness, was pressed onto the metal plate and cured under heating conditions of 100°C for 30 min followed by 65°C for 60 min. The thickness of the resin was controlled with glass plate spacers of different thicknesses. Distance “a” (shown in Fig. 2) was measured for three specimens of each resin thickness, using a profile projector to provide an indicator of the distortion after curing of the resin. The data was treated statistically by ANOVA with Tukey’s test.

3. Distortion of metal frame simulating an anterior arch Metal frames simulating an anterior arch of a six-unit bridge were made from Au-Ag-Pd-Cu alloy by casting. The thickness of the basal metal plane was varied, values of 0.7 mm, 1.0 mm, 1.2 mm, 1.4 mm, 1.7 mm,
Fig. 2 Plate-shaped alloy frame for distortion measurements with different thicknesses of heat-cured type acrylic resin containing 4-META. The surfaces of some specimens were subjected to a surface treatment (Adlloy modification) before application of the resin. The distance “a” was used as an indicator of the distortion after curing the resin.

Fig. 3 Metal frame for distortion measurements simulating an anterior arch of a six-unit bridge with facing resin. After treatment with a metal primer and application of about 0.1 mm thick opaque resin on the metal frame, a facing composite 1.5 mm thick resin was applied on the opaque resin. 2.1 mm, and 2.8 mm were used, as shown in Fig. 3. Retention beads, 0.1 mm in diameter, were attached to the outer surface of the metal frame to strengthen the mechanical retention of the facing composite resin. An opaque resin, about 0.1 mm thick, was applied to the metal frame after treatment with a metal primer. A facing composite resin was applied with a thin wrapping film to about 1.5 mm in thickness on the opaque resin. Distance “b” shown in Fig. 4 was measured using a profile projector after the casting, curing of the resin, and trimming the resin to a tooth profile.

4. Observation of crack formation between the crowns of the facing composite resin after curing and trimming to a tooth profile
Metal frames simulating an anterior arch with a 0.7-mm-thick basal metal plane were used to clarify the formation mechanism of the cracks in the facing composite resin using the same procedure described above. The 0.7-mm-thick basal metal plane was selected as the thickness between the crowns of a long span bridge used clinically varies from 0.7 mm to 2.0 mm but is generally near 1.0 mm. The distance “b” was measured for twelve different specimens after casting and before and after trimming the facing composite resin. The cracking between the crowns of the facing composite resin was observed by the naked eye after trimming the tooth profile.

RESULTS
Observation of distortion of the metal frame
1. Ring-shaped specimen
Figure 5 shows the ring-shaped specimen after cutting with a diamond saw blade. Figure 5 (a) shows the specimen with Adlloy surface modification for adhesion, (b) the specimen with no modification for adhesion, and (c) the metal ring without resin. Specimen (a) showed a separation of 7 mm immediately after cutting. Specimens (b) and (c) showed a separation of the metal of only 0.5 mm (which is the thickness of the diamond saw blade). However, the separation of the resin shown by the white thick arrow in (b) is larger than that of the metal. The results show that a large separation arises when the resin adheres to the alloy.

2. Plate-shaped specimen
Figure 6 shows the relationship between the distortion (distance “a” shown in Fig. 2) and the thickness (1, 2, or 3 mm) of 4-META resin. The values were statistically significantly different by the ANOVA with Tukey’s test ($p<0.05$), indicating increasing distortion with decreasing thickness of resin.
3. Distortion of metal frame simulating an anterior arch with a facing composite resin

Figure 7 shows the relationship between distortion (distance “b” shown in Fig. 4) and thickness of the metal frame for the cured specimens with different thicknesses of the basal metal plane before trimming the resin to a tooth profile. The value at 0.7 mm in thickness was obtained from an average of twelve specimens and the other values were obtained from one specimen each. Distortion of the metal frame decreased with increasing thickness of the metal frame.

Figure 8 shows the distortion (distance “b”, Fig. 4) obtained from the cured specimen with a facing composite resin layer on a 0.7-mm-thick basal metal plane. The cured composite resin was trimmed to 1.5 mm thickness with a carborundum point and a polishing point to give a tooth buccal profile following clinical procedures. The distance “b” was measured before and after the trimming of the resin. The original distance of 35.0 mm changed to 36.2 mm after curing of

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**Fig. 5**  Ring-shaped alloy specimen for the distortion measurements.  
The ring was cut with a 0.5 mm thick diamond saw blade after curing a 1-mm-thick layer of heat-cured acrylic resin containing 4-META onto the outer surface of the ring.  
(a) surface modification for adhesion with Adlloy,  
(b) no modification, and (c) metal ring without resin.

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**Fig. 6**  Relationship between distortion (distance “a” shown in Fig. 2) of a 0.3-mm-thick plate-shaped metal frame and thicknesses of heat-cured acrylic resin containing 4-META.  
The values were significantly different by ANOVA with Tukey’s test ($p<0.05$).

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**Fig. 7**  Relationship between distortion after curing (distance “b” shown in Fig. 4) and thickness of the basal metal plane.

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**Fig. 8**  Distortion (distance “b” shown in Fig. 4) obtained with a 0.7-mm-thick basal metal plane after curing or after curing and trimming to a tooth profile.  
The curvature of the metal frame recovered towards the original shape after trimming the resin to a tooth profile.
Fig. 9 Crack formed on a clinical long span bridge.

Fig. 10 Relationship between distortion (distance “b” shown in Fig. 4) obtained with a 0.7-mm-thick basal metal plane and the number of cracks formed between the crowns adjacent to the facing composite resin after curing and trimming to a tooth profile.

Distortion of the curvature of the metal frame recovers towards the original shape with increasing numbers of cracks. The data was obtained from twelve specimens: for zero and one crack from two specimens each, for two and three cracks from three specimens each, and for four and five cracks from one specimen each.

4. Cracking between the crowns of the facing composite resin after curing and trimming to a tooth profile

Figure 9 shows a typical crack in the proximal surface of the resin on the clinical long span bridge with resin facing formed during usual dental laboratory procedures. Figure 10 shows the relationship between the distance “b” and the number of cracks generated in the facing composite resin between the crowns after trimming to a tooth profile. The data were obtained from twelve specimens of the 0.7 mm basal metal plane by taking the average values of two specimens for each of the crack numbers 0 and 1, three specimens for each of the crack numbers 2 and 3, and one specimen for each of the crack numbers 4 and 5. The curvature was increasingly recovered as the crack numbers increased.

**DISCUSSION**

Metal frame distortion due to polymerization shrinkage and thermal contraction could be visualized with a simple ring-shaped specimen as shown in Fig. 5. After cutting with a diamond saw, the distance of the metal after cutting remained at the saw blade thickness of 0.5 mm for the samples without Adlloy treatment for adhesion, although the distance of the resin is larger than that of the metal. However, the distance of the Adlloy-treated specimen (a) was 7 mm, indicating that the distortion of the metal frame was larger when adhesion had occurred. The stress induced in the resin by polymerization shrinkage and thermal contraction also becomes a driving force for breaking the adhesive bond and for distortion of the metal frame.

Distortion of the metal frame increased with decreasing thickness of the 4-META resin as shown in Fig. 6. This can be explained on the basis of the geometrical moment of inertia, I, as follows: The bending rigidity is the product, I×E, of I and a modulus of elasticity, E. The geometrical moment of inertia, I, is represented by the formula (1):

\[
I = bh^3/12
\]  

(1)

where h is height and b width of a rectangular cross section. Larger I×E values indicate greater stiffness. Bending rigidities are 0.08b×E for the 1.0 mm thickness, 0.67b×E for the 2.0 mm thickness, and 2.25b×E for the 3.0 mm thickness. Since the width and modulus of elasticity are the same, the bending rigidity varies with the third power of the thickness, h^3, and the bending rigidity for a 3-mm-thick specimen is 27 times larger than that of a 1-mm-thick specimen. Although the bending force caused by the polymerization shrinkage and thermal contraction may be higher with increasing thickness of the resin, the bending rigidity also increases, as described above. The overall effect is that the increase in bending rigidity overcomes the increased bending force upon curing. The same trend was found in the relationship between distortion and thickness of the metal frame simulating an anterior arch with a facing composite resin as shown in Fig. 7.

Minute cracks on the proximal surface of the facing resin were also observed macroscopically for the samples with a metal frame simulating an anterior arch of a six-unit bridge with facing resin. The curvature of the dental arch recovers towards the original shape...
The mechanism of formation of the cracks between the crowns of a facing composite resin after curing and trimming to a tooth profile is depicted in Fig. 11. The curvature of the metal frame is recovered after trimming the facing composite resin by the elastic recovery of the metal frame with associated crack formation. With increasing number of cracks as shown in Fig. 10. Figure 11 shows the mechanism of formation of the cracks between the crowns of a facing composite resin after curing and trimming to a tooth profile. The curvature of an anterior arch simulating a six-unit bridge with a facing composite resin is opened by shrinkage of the resin after curing (a). Elastic recovery of the structure occurs due to the bending moment of the metal. The cracks are formed by the elastic recovery of the metal frame after trimming the facing composite resin to a tooth profile using a carborundum point and a polishing point as in clinical procedures (b). The release of the internal stress occurs simultaneously with the crack formation. A facing composite resin offers many advantages such as ease of formation, handling, and color matching. However, minute cracks may form on the proximal surface of the resin with a long span bridge during dental laboratory procedures as shown in Fig. 9.

When cracks do not form after trimming of the tooth profile, cracks may subsequently occur on the proximal surfaces during adaptation of the metal frame to the dental arch gypsum model. Although the fit of the metal frame to the model is improved by the formation of cracks, this gives rise to new problems such as peeling of the resin from the metal frame. Repairing the cracks is a required procedure when cracks form on the proximal surfaces. The crack formation in a facing composite resin could be prevented using a thicker basal metal plane of the metal frame as described in eq. (1).

Two types of resin, a heat-cured type acrylic resin and a facing composite resin were used in the present visualization study. The amount of polymerization shrinkage and thermal contraction is considered to be different as these resins consist of different components. The amount of thermal contraction also depends on the coefficient of thermal expansion with the amounts of resin involved and the kinds of organic components in the resin. The amount of polymerization shrinkage depends on amounts and kinds of monomer. The facing composite resin used in the present study contained an organic component of about 44% as determined by a burning test. Although the heat-cured type acrylic resin contains about 33% monomer, the monomer content in the facing composite resin is not clear. A further detailed study needs to clarify the monomer and filler contents in the facing composite resin.

CONCLUSIONS

Three types of specimens, a ring-shaped specimen, a plate-shaped specimen, and a metal frame simulating an anterior arch, were used to observe metal frame distortion with resin. Measurements of distortion of the metal frames with two types of resin, a 4-META resin and a light-curing facing composite resin, with adhesion between the metal frame and resin were carried out in this study. The results obtained may be summarized as follows:

1. Metal frame distortion due to polymerization shrinkage and thermal contraction of a heat-curing 4-META resin could be visualized with the simple ring-shaped specimen. The rings were cut with a diamond saw, and after cutting the gap created by the sawing remained at the saw blade thickness when there was no resin on the metal frame, but opened significantly when adhering resin had been applied.

2. For the plate-shaped specimens, distortion after curing decreased with increasing thickness of 4-META resin.

3. After curing of the facing composite resin, the curvature of the metal frame simulating an anterior arch of a six-unit bridge with a facing composite resin widened due to polymerization shrinkage and thermal contraction of the composite resin and the widening decreased with increasing thickness of the metal frame. The curvature decreased by the elastic recovery of the metal frame after trimming the facing composite resin and recovered towards the original shape with increasing numbers of cracks formed in the composite resin between the crowns.

REFERENCES

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