ORIGINAL ARTICLE

Effect of reinforcement on the flexural properties of injection-molded thermoplastic denture base resins

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Short title: Effect of reinforcement on thermoplastic denture base

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Abstract

Purpose: This study evaluated the effect of reinforcement on the flexural properties of injection-molded thermoplastic denture base resins.

Materials and methods: Three injection-molded thermoplastic denture base resins (polyamide, polyester, polycarbonate) were selected for this study, and a conventional heat- polymerized denture base resin (PMMA) was used as a control. Continuous unidirectional glass fiber-reinforced composite (FRC) and metal wire were used for reinforcement. The reinforced bar-shaped specimens (65 mm long, 10 mm wide and 3.3 mm high) were fabricated (n=10). The flexural strength at the proportional limit (FS-PL) and the elastic modulus were measured with a three-point bending test.

Results: All the denture base material specimens reinforced with FRC possessed a significantly higher FS-PL compared with those without reinforcement. The FS-PL of the polycarbonate specimens reinforced with metal wire was significantly higher than that without reinforcement, and there was no significant difference in the FS-PL between the polycarbonate specimens reinforced with FRC and those with metal wire. The descending order of the elastic modulus according to the denture base material, arranged in terms of statistical significance, was: PMMA (3.46 ± 0.53 GPa) > polycarbonate (2.69 ± 0.48 GPa) > polyester (2.00 ± 0.39 GPa) > polyamide (1.14 ± 0.35 GPa). The descending order of the elastic modulus according to the reinforcement, arranged in terms of statistical significance, was: metal wire (2.74 ± 0.96 GPa) > FRC (2.40 ± 0.89 GPa) > no reinforcement (1.82 ± 0.83 GPa).

Conclusion: Continuous unidirectional glass fiber-reinforced composite (FRC) reinforcement had satisfactory reinforcing effect for injection-molded thermoplastic denture base resins.

Key Words: polyamide, polyester, polycarbonate, fiber reinforced composite

Introduction

A removable partial denture includes components that prevent displacement of the prosthesis from the patient's mouth during function. In general, there are two types of direct retainers: intracoronal direct retainers and extracoronal direct retainers. Retentive metal clasp assemblies represent the most common method for extracoronal direct retention.[1] Generally, a metal clasp is used to retain and stabilize a removable partial denture.[2] However, the location of the metal clasps may affect the aesthetics, e.g., the anterior and premolar teeth region. Recently, a removable partial denture without metal clasps was used in dental practice.[3-5] The entire structure of the denture, except for the artificial teeth, is made from a denture base resin and is integrated. The clinical purpose of the prosthesis is that problems resulting from the metal clasps, such as poor aesthetics and metal allergies, can be eliminated.[6] The prosthesis is retained at the undercuts of the abutment teeth using retentive arms made from denture base resin, and the retentive arms are deflected during the insertion and removal of the denture. Injection-molded thermoplastic resins are used for the removable partial denture without metal clasps because these thermoplastic resins have a higher elasticity compared to a conventional heat-polymerized denture base resin (PMMA). The flexibility of the injection-molded thermoplastic resin is important because it affects the ease of insertion and removal of the removable partial denture without metal clasps as well as its retention and the stress to the abutment teeth.[7,8] Nevertheless, since a denture base is placed on the soft tissue and underlying hard tissue, it is preferable for the denture base to remain stiff and undergo little deflection during chewing.[7]

Injection-molded thermoplastic resins for a denture base material have been investigated, and the flexural properties of injection-molded thermoplastic denture base resins were studied.[7-13] Previous studies[7,8,12] found that injection-molded thermoplastic denture base resins had a significantly lower elastic modulus and a significantly lower flexural strength at the proportional limit (FS-PL) compared with the conventional heat-polymerized acrylic denture base resin (PMMA). These properties mean that injection-molded thermoplastic denture base resins are flexible and weak materials compared to PMMA. Flexible materials are acceptable for the retentive arms of a removable partial denture without metal clasps. However, flexible and weak materials are not acceptable for the denture base of a removable prosthesis because findings indicate that a denture base tends to undergo permanent deformation during mastication and then the cancellous bone under the denture base will be absorbed if vertical stress occurs from the deformation.

With regard to the failure record of acrylic resin removable dentures, a clinical study[14] reported that 68% of dentures had broken by the end of three years after placement. Another clinical study[15] found that 28% of dentures underwent repair during the first year of use, and 39% required repair during the first three years of use. To prevent such clinical fracture, metal wire reinforcements have conventionally been used to strengthen acrylic resin dentures and have been investigated.[16-23] Likewise, glass fibers have been employed to reinforce acrylic resin dentures and have been studied for more than 20 years.[16,19,21,24-33] Regarding glass fiber reinforcement, the denture base can be strengthened with fibers in two ways: the entire base can be reinforced with a fiber weave (total fiber reinforcement) or a fiber reinforcement can be placed precisely at the weakest part of the denture (partial fiber reinforcement).[34,35] If the fiber reinforcement is incorporated into the denture during repair, the partial fiber reinforcement is the reinforcement of choice because it is easier to handle than the total fiber reinforcement.[34] In addition, the partial fiber reinforcement can prevent recurrent fractures in acrylic resin dentures.[35] As stated above, reinforcements for acrylic resin dentures have already been studied. Similarly, reinforcing removable partial dentures without metal clasps must be examined as well. However, there is presently insufficient information about this subject.

The purpose of this study was to investigate the effect of reinforcement on the flexural properties of injection-molded thermoplastic denture base resins. The null hypothesis was that the reinforcements would not affect the flexural properties of the injection-molded thermoplastic denture base resins.

Materials and Methods

Three injection-molded thermoplastic denture base resins were selected for this study, and a conventional heat polymerized denture base resin (PMMA) was used as a control (Table 1). The flexural properties of the denture base materials were measured according to ISO 20795-1:2008.[36]

Each reinforced denture base material specimen was fabricated for flexural properties, and a specimen without reinforcement was fabricated as a control (n=10). Metal wire (65 mm long) and continuous unidirectional glass fiber-reinforced composite (FRC, 65 mm long, Figure 1) were used for reinforcement (Table 2). The FRC was polymerized with a light-curing unit (UnixS II, Heraeus Kulzer, Wehrheim, Germany) for 3 min. Each reinforcement was placed longitudinally in the center of the specimens. Each specimen was polymerized in molds with cavities (65 mm long, 10 mm wide and 3.3 mm high) according to the manufacturer's instructions. The specimens were then polished with 600-grit SiC paper. The accuracy of the dimensions was verified with a micrometer at three locations for each dimension to within a 0.05-mm tolerance for width and height. The specimens were stored in water at 37ºC for 50 ± 2 hours before testing.

The flexural strength at the proportional limit (FS-PL) and the elastic modulus of the specimens were tested. Each specimen was placed on a 50-mm-long support for three-point flexural testing. A vertical load was applied using a load-testing machine (ASG-J; Shimadzu Co. Ltd., Tokyo, Japan) at the midpoint of the specimen at a crosshead speed of 5 mm/min. The FS-PL (MPa) was calculated using the following formula:

$$\text{FS-PL} = 3Fl/2bh^2$$

where F = the load (N) at the proportional limit, l = the distance (50 mm) between the supports, b = the width (mm) of the specimen and h = the height (mm) of the specimen. The load at the proportional limit was determined from each load/deflection graph.

The elastic modulus (GPa) was calculated according to the following formula:

$$\text{Elastic modulus} = F_1 l^3 / 4bh^3 d$$

Where F_1 = the load (N) at a point in the straight line portion of the load/deflection graph and d = the deflection (mm) at load F_1.

All tests were performed under uniform atmospheric conditions of 23.0 ± 1ºC and 50 ± 1% relative humidity.

A two-way analysis of variance (ANOVA) (STATISTICA, StatSoft Inc., Tulsa, OK) was applied to study the difference among the denture materials and the reinforcements. A one-way ANOVA (STATISTICA) was applied if there was a significant difference resulting from the interaction between these two variables ($p<0.05$). The Newman-Keuls post-hoc comparison ($p=0.05$) (STATISTICA) was applied when appropriate.

Micrographs of the cross sections of representative specimens of the reinforced denture base resin were taken at 200x magnification using a scanning electron microscope (SEM, JSM-6330F, JEOL, Tokyo, Japan) to study the quality of the interface between the reinforcement and the denture base resin.

Results

The two-way ANOVA revealed that there were significant differences in the FS-PL caused by the variables of the denture base material and the reinforcement and their interaction ($p<0.05$). The one-way ANOVA and the Newman-Keuls post-hoc comparison were applied to each denture base material/reinforcement combination. The results are depicted in Table 3 and Figure 2. All the denture base material specimens reinforced with FRC possessed significantly higher FS-PL compared with those without reinforcement. The FS-PL of the polycarbonate specimen reinforced with metal wire was significantly higher than that without reinforcement, and there was no significant difference in the FS-PL between the polycarbonate specimen reinforced with FRC and that with metal wire.

The two-way ANOVA revealed that there were significant differences in the elastic modulus caused by the variables of the denture base material and the reinforcement ($p<0.05$), and there was no significant difference in the elastic modulus because of the interaction between the denture base material and the reinforcement ($p>0.05$). The descending order of the elastic modulus according to the denture base material, arranged in terms of statistical significance, was: PMMA (3.46 ± 0.53 GPa) > polycarbonate (2.69 ± 0.48 GPa) > polyester (2.00 ± 0.39 GPa) > polyamide (1.14 ± 0.35 GPa). The descending order of the elastic modulus according to the reinforcement arranged in terms of statistical significance was: metal wire (2.74 ± 0.96 GPa) > FRC (2.40 ± 0.89 GPa) > no reinforcement (1.82 ± 0.83 GPa). The mean and standard deviation of the elastic modulus of the denture base material/reinforcement groups are depicted in Table 4 and Figure 3.

SEMs of representative reinforced specimens showed cross sections of the interface between the reinforcement and the denture base resin (Figures 4, 5). SEMs of the interface of all the denture base resin specimens showed good contact to the metal wire (Figure 4). The contact of the interface between FRC and three injection-molded denture base resins was generally good. The SEM view of the interface of a representative PMMA specimen indicated good contact to FRC.

Discussion

The null hypothesis of this study was rejected, and the reinforcements affected the flexural properties of injection-molded thermoplastic denture base resins.

In the majority of previous studies, the flexural strength of acrylic denture base resin has been evaluated at the ultimate load or at the fracture load. Dental plastics typically exhibit considerable plastic deformation before failure. The plastic deformation of a material beyond its proportional limit permanently alters the dimensions of the material. Therefore, plastic deformation is unacceptable for dental materials such as denture base materials that rely on dimensional stability as a prerequisite to their use.[37] A denture material should have a proportional limit sufficiently high so that permanent deformation does not result from the stress applied during mastication.[38] Therefore, the estimation of the proportional limit of a material using its resistance to plastic deformation is of significant clinical value. Several studies[37,39-42] have evaluated the resistance of denture base resins to plastic deformation under a flexural load. Likewise, in this study, the flexural strength at the proportional limit (FS-PL) of reinforced injection-molded thermoplastic denture base resins was investigated.

In the present study, the FS-PL of the conventional acrylic denture base resin reinforced with FRC was significantly higher than the FS-PL of the unreinforced acrylic denture base resin; the result was similar to that in the previous study.[22] Furthermore, the FS-PLs of all injection-molded thermoplastic denture base resins reinforced with FRC were significantly higher than the FS-PLs of unreinforced injection-molded thermoplastic denture base resins. However, in the present study, the FS-PL of the conventional acrylic denture base resin reinforced with metal wire was not significantly different from the FS-PL of the unreinforced acrylic denture base resin; the result was similar to the previous study.[22] Moreover, the FS-PLs of two injection-molded thermoplastic denture base resins, polyamide and polyester, reinforced with metal wire were not significantly different from the FS-PLs of unreinforced injection-molded thermoplastic denture base resins. Metal wire reinforcement merely showed the reinforcing effect of the polycarbonate in injection-molded thermoplastic denture base resins. Among these results, there was a difference between metal wire and FRC in the FS-PL; nevertheless, the SEM views of the interfaces of all the denture base resin specimens showed good contact to the reinforcements. These results seem to indicate that FRC reinforcement tended to be effective compared to metal wire reinforcement for the injection-molded thermoplastic denture bases in the FS-PL. This finding may be due to the bonding of FRC reinforcements to the denture base resin and the entanglement of FRC reinforcements in the denture base resin, while the metal reinforcement did not bond completely to the denture base resin. Consequently, FRC reinforcement was incorporated into the denture base and the reinforced denture showed higher FS-PL.

The different strength of the polycarbonate denture base resin reinforced with metal wire compared with other injection-molded thermoplastic denture base resins reinforced with metal wire may be due to differences in the barrel temperature of the thermoplastic denture base resins at the time of injection molding. The barrel temperature of the polycarbonate (320ºC) is higher than that of polyamide (215ºC) and polyester (280ºC) (see Table 1); therefore, material with a higher barrrel temperature has good flow into every detail, and furthermore, after molding, the thermal shrinkage of the polycarbonate is larger than for the others. Thus, in the present study, it seems that the metal wire reinforcement was tightly combined with the polycarbonate in mechanical; as a result, the polycarbonate denture base resin reinforced with metal wire had a higher FS-PL than other injection-molded thermoplastic denture base resins reinforced with metal wire. Regarding the metal wire reinforcement for acrylic resin denture base resins, a previous study[17] reported that it was effective to sandblast the metal wire reinforcement to improve the fracture resistance of acrylic resin denture base resins. Another previous study[18] reported that the chemical bonding method could improve the adhesion between the metal wire strengthener and the acrylic denture base resin to enhance the fracture resistance of the acrylic denture base construction. Nevertheless, there is currently insufficient information about the adhesion between metal wire reinforcements and injection-molded thermoplastic denture base resins. Thus, it seems that further studies are necessary about the effect of surface treatment of metal wire reinforcement on the FS-PL of injection-molded thermoplastic denture base resins.

With regard to the elastic modulus of reinforced denture base material, the descending order of the elastic modulus according to the denture base material in the present study, arranged in terms of statistical significance, was: PMMA > polycarbonate > polyester > polyamide. This order was similar to that in previous studies[7,11] regarding injection-molded thermoplastic denture base resins without reinforcement and acrylic denture base resins without reinforcement. Furthermore, in the present study, the descending order of the elastic modulus according to the reinforcement, arranged in terms of statistical significance, was: metal wire > FRC > no reinforcement. Likewise, previous studies[29,32] reported that acrylic denture base resin reinforced with FRC had a significantly higher elastic modulus than that without reinforcement. The reason for these results could be explained by the elastic moduli of the intact reinforcement and bulk denture base resin. The elastic moduli of intact metal wire reinforcement and intact FRC reinforcement used in this study were 153.2 GPa (see Table 2) and 26.1 GPa [43], respectively, and the elastic moduli of bulk denture base resins were 0.70-2.92 GPa (see Table 4). Therefore, the general descending order of the elastic moduli of the intact reinforcement and bulk denture base resin is: intact metal wire reinforcement > intact FRC reinforcement > bulk denture base resins. Hence, these elastic moduli affected the elastic moduli of the reinforced denture base resins; as a result, these reinforced denture base resins became stiffer than the unreinforced denture base resins.

The results of the present study that most affected the clinical, injection-molded thermoplastic denture base resins were the significantly lower resistance to plastic deformation compared to conventional acrylic denture base resins. As mentioned earlier, this finding indicates that a denture base made from the injection-molded thermoplastic denture base resin tends to undergo permanent deformation during mastication, and then the cancellous bone under the denture base will be absorbed if vertical stress occurs from the deformation. In order to improve the resistance to plastic deformation, the reinforcements had a reinforcing effect on the injection-molded thermoplastic denture base resins in the present study. Especially, the FRC reinforcement improved the resistance to the plastic deformation of all the injection-molded thermoplastic denture base resins used in the present study. Moreover, metal wire reinforcement and FRC reinforcement caused stiffness in all injection-molded thermoplastic denture base resins used in the present study, which is clinically acceptable. Clinically, the FRC reinforcement is thus preferable to metal wire reinforcement for removable partial dentures without metal clasps. As mentioned above, it is preferable for the denture base of the removable partial denture without a metal clasp to remain stiff and undergo little deflection during chewing; thus, the prosthesis should be constructed to have optimum strength.

Conclusions

Under the conditions of the present experimental study, the following conclusions may be drawn:

(1) The continuous unidirectional glass fiber-reinforced composite (FRC) reinforcement had a reinforcing effect on the polyamide, the polyester and the polycarbonate denture base resins.

(2) Metal wire reinforcements had a reinforcing effect on the polycarbonate denture base resin.

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Acknowledgements

The authors would like to thank the GC Corporation for supplying some of the materials used in this project.

Table 1 Denture base resins used in this study.

Constituent	Material	Manufacturer	Lot number	Processing method
Polyamide	Valplast	Unival Co., Ltd. Tokyo, Japan	111100	Injection molding technique; heat processed at 215ºC for 20 min
Polyester	EstheShot Bright	i-Cast Co. Ltd., Kyoto, Japan	2A6775120	Injection molding technique; heat processed at 280ºC for 20 min
Polycarbonate	Reigning N	Toushinyoukou Co. Ltd., Niigata, Japan	HSE19T	Injection molding technique; heat processed at 320ºC for 30 min
Polymethyl methacrylate (PMMA)	Acron	GC Corp., Tokyo, Japan	(P)1401211 (L)1401291	Heat-polymerized,compression molding technique; heat-processed at 70ºC for 90 min, then at 100ºC for 30 min

Table 2 Reinforcements used in this study.

Brand	Manufacturer	Lot number	Composition
Sun-Cobalt Clasp-Wire	Dentsply-Sankin K.K., Tochigi, Japan	710171	Co-Cr-Ni clasp wire, 1.2 mm diameter. Co (46%), Cr (20%), Ni (22%), W (4%), Mo (3%), Mn (2%), Fe (3%). Elastic Modulus;152.3 GPa.
everStick C&B	GC Corp., Tokyo, Japan	140704	Continuous unidirectional fiber bundle, 1.5 mm diameter. E-glass fiber impregnated with PMMA and bis-GMA. 4000 individual glass fibers in one bundle.

Table 3 Mean and standard deviation (SD) of the flexural strength at the proportional limit (MPa) of the denture base material/reinforcement groups (n=10).

Denture base resin	Reinforcement	Flexural strength at proportional limit (MPa)
Polyamide (Valplast)	none	11.5(1.2)^{f}
Polyamide (Valplast)	metal	14.2(1.1)^{f}
Polyamide (Valplast)	FRC	18.6(0.6)
Polyester (EstheShot Bright)	none	26.8(1.5)^{e}
Polyester (EstheShot Bright)	metal	29.9(2.5)^{d,e}
Polyester (EstheShot Bright)	FRC	41.7(4.4)^{a}
Polycarbonate (Reigning N)	none	29.2(1.2)^{d,e}
Polycarbonate (Reigning N)	metal	36.8(3.4)^{c}
Polycarbonate (Reigning N)	FRC	36.7(0.8)^{b,c}
PMMA (Acron)	none	30.9(4.2)^{d}
PMMA (Acron)	metal	31.2(3.2)^{d}
PMMA (Acron)	FRC	39.9(7.6)^{a,b}

The same letter denotes groups that were not significantly different from each other (p>0.05)

Table 4 Mean and standard deviation (SD) of the elastic modulus (GPa) of the denture base material/reinforcement groups (n=10).

Denture base resin	Reinforcement	Elastic modulus (GPa)
Polyamide (Valplast)	none	0.70(0.02)
Polyamide (Valplast)	metal	1.50(0.19)
Polyamide (Valplast)	FRC	1.22(0.08)
Polyester (EstheShot Bright)	none	1.51(0.03)
Polyester (EstheShot Bright)	metal	2.37(0.16)
Polyester (EstheShot Bright)	FRC	2.13(0.15)
Polycarbonate (Reigning N)	none	2.13(0.03)
Polycarbonate (Reigning N)	metal	3.17(0.31)
Polycarbonate (Reigning N)	FRC	2.76(0.23)
PMMA (Acron)	none	2.92(0.12)
PMMA (Acron)	metal	3.94(0.36)
PMMA (Acron)	FRC	3.51(0.44)

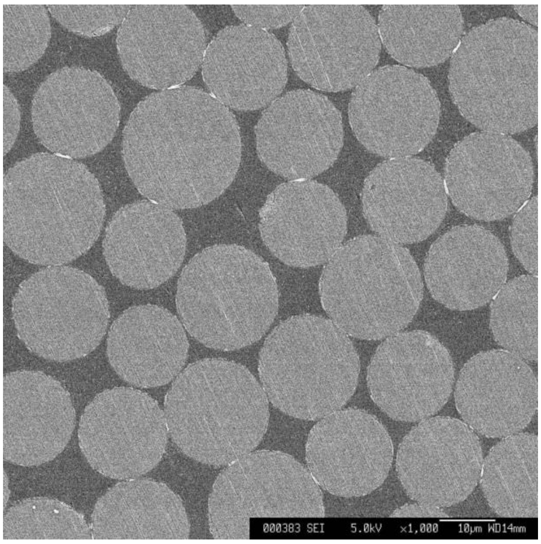


Figure 1 Scanning electron micrograph (x 1,000) of cross section of polymerized FRC reinforcement.

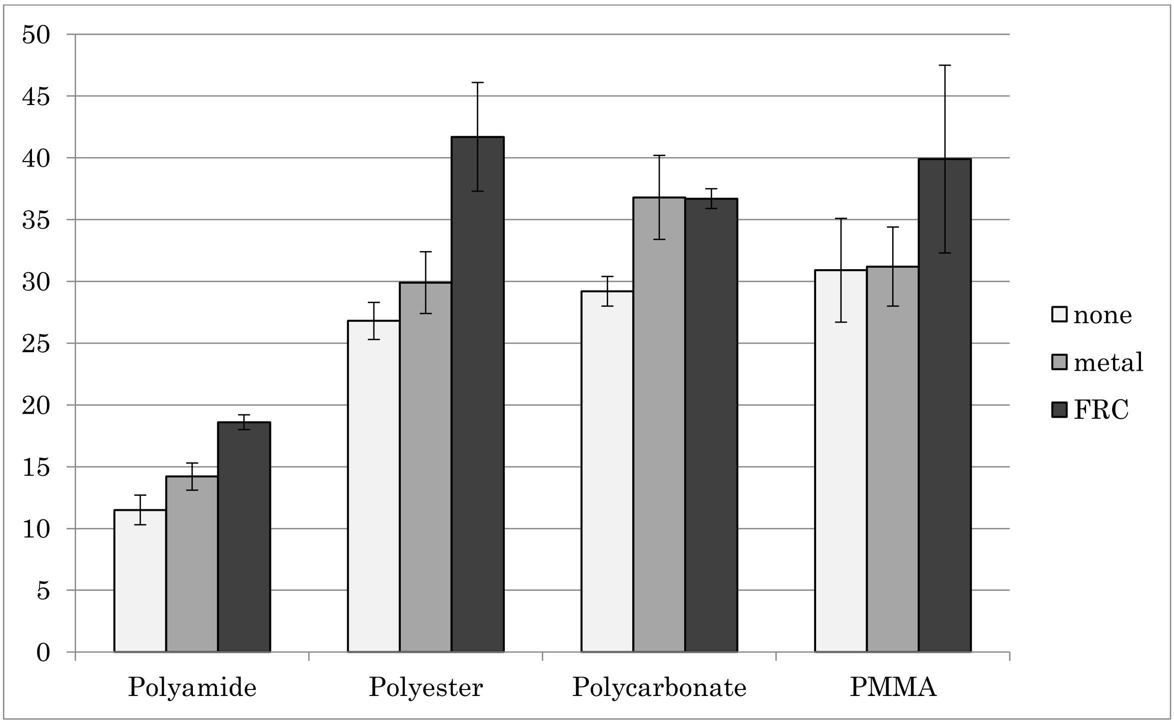


Figure 2 Mean flexural strength at proportional limit (MPa) and standard deviation of the reinforced denture base materials.

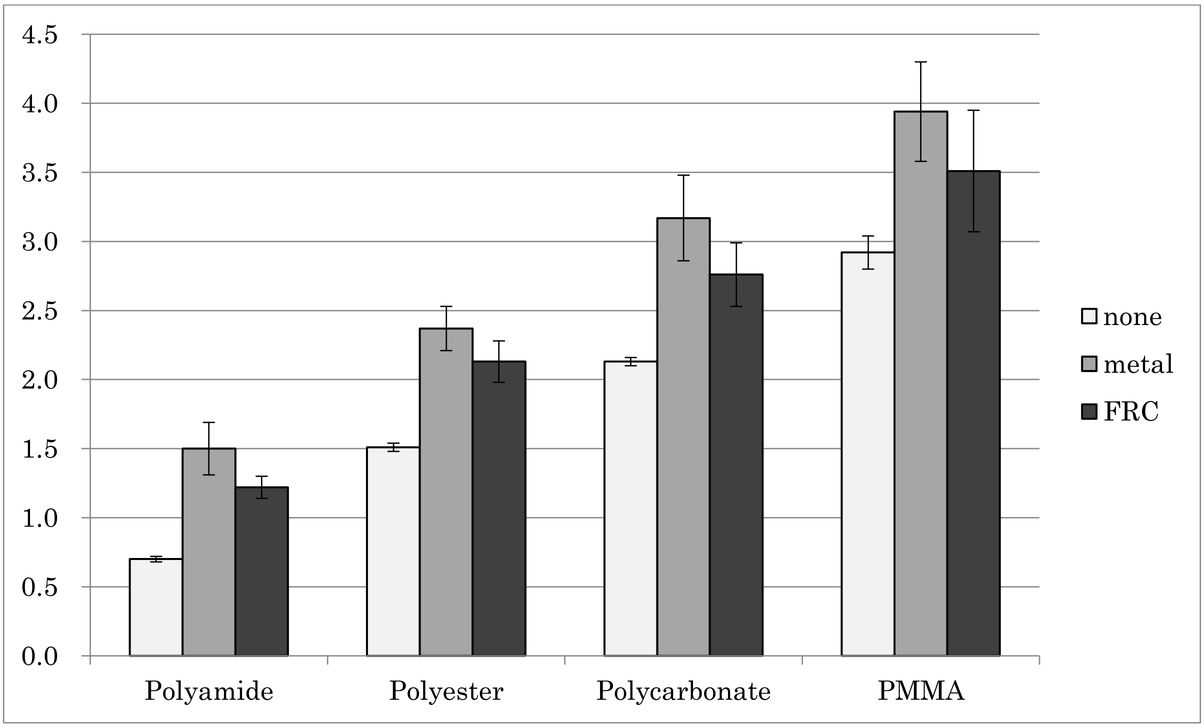
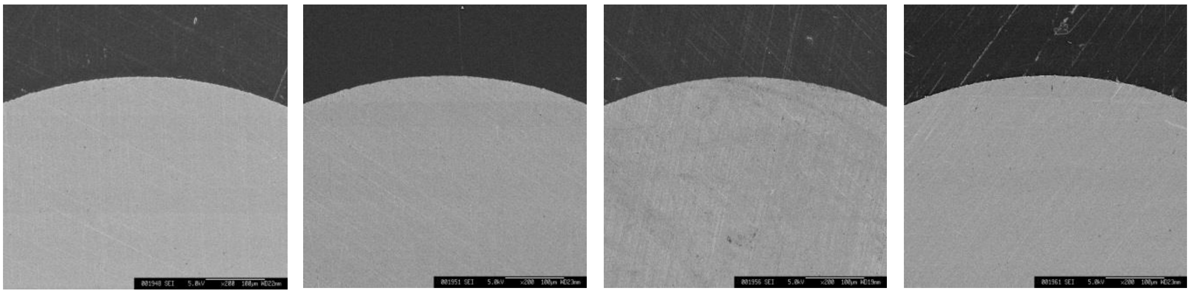
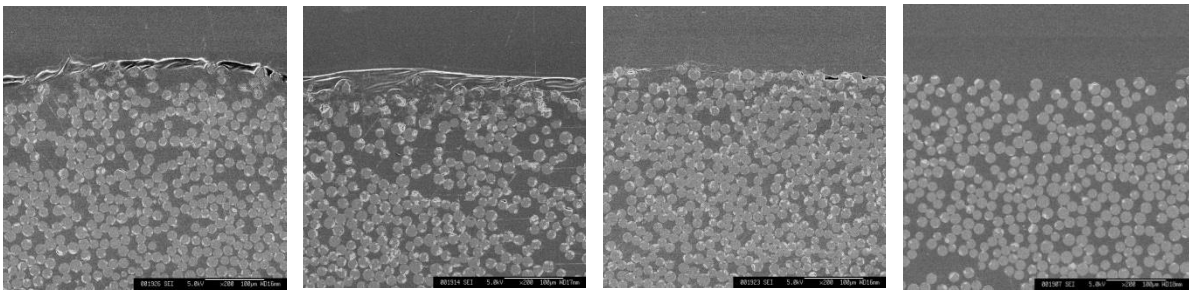


Figure 3 Mean elastic modulus (GPa) and standard deviation of the reinforced denture base materials.



Polyamide Polyester Polycarbonate PMMA

Figure 4 Scanning electron micrographs (x 200) of cross section of the interface between metal wire and denture base material; upper part: denture base material, lower part: metal wire.



Polyamide Polyester Polycarbonate PMMA

Figure 5 Scanning electron micrographs (x 200) of cross sections of the interface between FRC and denture base material; upper part: denture base material, lower part: FRC.