©Operative Dentistry, 2021, **46-3**, E117-E131

Flexural Properties and Polished Surface Characteristics of a Structural Colored Resin Composite

K Mizutani • T Takamizawa • R Ishii • S Shibasaki
H Kurokawa • M Suzuki • A Tsujimoto • M Miyazaki

Clinical Relevance

Polishing the structural colored resin composite Omnichroma with an aluminum oxide flexible disk after finishing with a tungsten carbide bur significantly improved its surface properties when compared with the other methods.

SUMMARY

Objective: The aim of this study was to determine the flexural properties and surface characteristics of a structural colored resin composite after different finishing and polishing methods, in comparison to those of conventional resin composites.

Methods and Materials: A structural color resin composite, Omnichroma (OM, Tokuyama Corp, Chiyoda City, Tokyo, Japan), and two comparison resin composites, Filtek Supreme Ultra (FS, 3M, St Paul, MN, USA) and Tetric EvoCeram (TE, Ivoclar Vivadent, Schaan, Liechtenstein), were used. The flexural properties of the resin composites were determined in accordance with the ISO 4049 specifications. For surface properties, 70 polymerized specimens of each resin composite were prepared and divided into seven groups of 10. Surface roughness (Sa), gloss (GU), and surface free energy (SFE) were investigated after the following finishing and polishing methods. Three groups of specimens were finished with a superfine-grit diamond bur (SFD), and three with a tungsten carbide bur (TCB). After finishing, one

Kiyoto Mizutani, DDS, Department of Operative Dentistry, Nihon University Graduate School of Dentistry, Tokyo, Japan
*Toshiki Takamizawa, DDS, PhD, Department of Operative Dentistry, Nihon University School of Dentistry, Tokyo, Japan
Ryo Ishii, DDS, PhD, Department of Operative Dentistry, Nihon University School of Dentistry, Tokyo, Japan
Sho Shibasaki, DDS, PhD, Department of Operative Dentistry, Nihon University School of Dentistry, Tokyo, Japan
Hiroyasu Kurokawa, DDS, PhD, Department of Operative Dentistry, Nihon University School of Dentistry, Tokyo, Japan
Miho Suzuki, DDS, Department of Operative Dentistry, Nihon University School of Dentistry, Tokyo, Japan
Akimasa Tsujimoto, DDS, PhD, Department of Operative Dentistry, University of Iowa College of Dentistry, Iowa City, IA, USA
Masashi Miyazaki, DDS, PhD, Department of Operative Dentistry, Nihon University School of Dentistry, Tokyo, Japan
*Corresponding author: 1-8-13, Kanda-Surugadai, Chiyoda-ku, Tokyo, Japan; e-mail: takamizawa.toshiki@nihon-u.ac.jp

http://doi.org/10.2341/20-154-L

of the two remaining groups was polished with a one-step silicone point (CMP), and the other with an aluminum oxide flexible disk (SSD). A group ground with SiC 320-grit was set as a baseline.

Results: The average flexural strength ranged from 116.6 to 142.3 MPa in the following order with significant differences between each value: FS > TE > OM. The average E ranged from 6.8 to 13.2 GPa in the following order with significant differences between each value: FS > TE > OM. The average R ranged from 0.77 to 1.01 MJ/mm^3 in the following order: OM > FS > TE. The Sa values of the OM groups polished with CMP and SSD were found to be significantly lower than those of the other resin composites, regardless of the finishing method. The GU values appeared to be dependent on the material and the finishing method used. The OM specimens polished with SSD showed significantly higher GU values than those polished with CMP. Most of the resin composites polished with SSD demonstrated significantly higher γS values compared to the other groups. Extremely strong negative correlations between Sa and GU in the combined data from the three resin composites and each resin composite and between Sa and γS in the OM specimens were observed; GU showed a strong positive correlation with γS in the same material.

Conclusion: These findings indicate that both flexural and surface properties are material dependent. Furthermore, the different finishing and polishing methods used in this study were observed to affect the Sa, GU, and SFE of the resin composites.

INTRODUCTION

In order to achieve esthetic dental restorations, the color matching ability of resin composites used to restore teeth is considered to be of utmost importance. However, in some instances, it is difficult to color match the restoration to the tooth as the latter's color depends on the location and the optical properties of the tooth substrate.[1] In order to mimic the color of the restored tooth, different shades of resin composites are mixed using the layering technique.[2,3] This technique consists of several filling steps, which require a certain amount of clinical skill to obtain the desired color.[4]

It is important to take into account both the esthetic and mechanical properties of the resin composite restoration and its durability in the oral environment.[5-7] The mechanical properties of a resin composite are closely related to its fracture resistance and wear behavior.[8,9] Changes in the surface properties of a restoration lead to staining, plaque accumulation, restoration degradation, and gingival inflammation.[10,11] Therefore, to obtain the desired esthetics and at the same time ensure its longevity, the polishing ability of the resin composite should be determined. Ishii et al.[12] have examined the surface properties of resin composites and reported that the surface free energy (SFE) might reflect some of the important characteristics of the material, as with surface topography evaluation.

Structural color is thought to be a chromogenic phenomenon in which the visible color is derived from the structural features of the substance at a scale comparable to or smaller than the wavelength of visible light.[13] In contrast to colorants such as pigments or dyes, substances that produce structural color do not have a color of their own, but they can display visible colors owing to light interferences generated by their ultrastructure.[14] These materials can be classified into two categories, iridescent and non-iridescent, in accordance with their optical properties. The iridescent color arises from photonic crystals, which have periodic structures with regular lengths of the order of the wavelength of visible light.[15] On the other hand, non-iridescent materials have angle-independent characteristics wherein the color impression is the same for different illuminations and observation angles.[16]

A new type of resin composite has been developed based on the structural color concept and the bottom-up nanotechnology used in making unique filler particles.[17] These fillers are in the form of spherical particles, having an average diameter of 260 nm, which produce the yellow to red color shades required to match the natural tooth color.[17,18] The refractive index of the uniformly sized spherical filler exceeds that of the resin matrix, leading to the expression of a stronger structural color due to the scattering of the incident light.[19] Using the structural colored resin composite has been seen to simplify the shade matching process and render it more cost-effective as it only requires a single universal shade to be used. Saegusa and others,[17] who evaluated the color-matching ability of the structural colored resin composite and compared it with conventional ones using artificial teeth, have confirmed the excellent color-matching ability of the structural colored material. In addition, they suggested that these might have the potential to fix any color mismatch caused by using conventional materials. However, little information is available about the mechanical and surface properties of this structurally colored resin composite. As the color of the composite is achieved through modification of the filler structure, there is a

possibility that these properties will differ from those of conventional resin composites, and the properties of these composites must be taken into account in clinical usage. Therefore, it is important to measure them.

This study aims to determine the mechanical properties of the structural colored resin composite based on a flexural strength test, which should help to understand the effects of different finishing and polishing procedures on the surface properties of this material. The surface properties were then examined in terms of surface free energy (SFE), surface roughness, and gloss measurements; morphological assessments were made via scanning electron microscopy (SEM). The null hypotheses were as follows: 1) the flexural properties of the structural colored resin composite would not differ from those of conventional resin composites, and 2) the surface properties of the structural colored resin composite would not be affected by the finishing and polishing methods and would not differ from those of the conventional resin composites.

METHODS AND MATERIALS

Study Materials

The structural colored resin composite, Omnichroma (OM, Tokuyama Dental, Tokyo, Japan), and two other conventional resin composites, Filtek Supreme Ultra (FS, 3M Oral Care, St. Paul, MN, USA) as a nanofilled resin composite and Tetric EvoCeram (TE, Ivoclar Vivadent, Schaan, Lichtenstein) as a nanohybrid resin composite, were used in this study (Table 1). A halogen-quartz-tungsten curing unit (Optilux 501; SDS Kerr, Danbury, CT, USA) was used to avoid any effects of the reported non-uniformity of light-emitting diode curing units.[20] The light irradiance (above 600 mW/cm^2) of the curing unit was confirmed using a dental radiometer (Model 100; SDS Kerr).

Flexural Strength Test

The flexural properties of the tested resin composites were examined as per the ISO 4049 specifications.[21] A transparent polymer matrix tape (Matrix tape and Dispenser, 3M Oral Care) was placed on a glass slide, and a stainless-split mold (25 × 2 × 2 mm) was positioned on it. The resin composites were then inserted into the mold and covered with the matrix tape. Pressure was manually applied to the composites using another glass plate. The mold was then positioned on a glass slide. The middle third of the specimen was irradiated for 30 seconds after which the remaining thirds were irradiated for 30 seconds each. The polymerized specimen was removed from the mold, and all the sides were polished using a 1200-grit SiC (Fuji Star type DCCS; Sankyo Rikagaku, Saitama, Japan) paper. The prepared specimens were stored in distilled water at 37 °C in the dark for 24 hours. Twelve specimens per test resin composite were subjected to the three-point bending test (span length = 20 mm) using a universal testing machine (model 5500R; Instron, Canton, MA, USA) at a crosshead speed of 1.0 mm/min until breaking point. The flexural strength (σ_F) and elastic modulus (E) were determined from the stress-strain curve created using built-in computer software (Bluehill ver. 2.5; Instron) connected to the testing machine. In addition, the modulus of resilience (R) was calculated using the following equation[22]:

$$R = \sigma_F{}^2/2E$$

Specimen Preparation for Surface Property Evaluation

The specimens were prepared in cylindrical Teflon molds (height = 2.0 mm, diameter = 10.0 mm). One end of the mold was sealed using the matrix tape, and the resin paste was condensed into the mold from the open end. The open end was then covered with the matrix tape, and pressure was applied, followed by light irradiation for 30 seconds with a curing unit. The polymerized specimen was removed from the mold and was later stored in the dark at 25 °C for 24 hours before finishing and polishing. Seventy specimens were prepared for each resin composite.

Finishing and Polishing Procedures

The specimens were randomly divided into seven groups (n=10 each). All specimens in the seven groups were ground flat with a 320-grit SiC paper under tap water. The specimens in three groups were finished using a superfine-grit diamond bur (SFD; SF102R, ISO #017; Shofu, Kyoto, Japan), and those from another three groups were finished using a tungsten carbide bur (TCB; FG7714, ISO #014; Kerr, Orange, CA, USA). Those in the remaining group were ground with SiC 320-grit grinding paper and set as the baseline (BAS).

The finishing procedures were performed using a high-speed handpiece (TwinPower Turbine; J. Morita Mfg, Kyoto, Japan) with water spray. Light hand pressure was applied in multiple directions, and the burs were changed after five uses. Three specimens, each from the three groups (SFD, TCB, and BAS), were set aside for measurements. Two specimens, one each from the SFD and TCB groups, were polished using the one-step point-type polishing system comprising a silicone polisher impregnated with a diamond particle (CMP; CompoMaster, Shofu). Likewise, two specimens (one each from the SFD and TCB groups)

Table 1: *Materials Used in this Study*

Code	Resin Composite (Lot No.)	Main Components	Type of Resin Composite (Filler Content)	Manufacturer
OM	Omnichroma (18B28)	UDMA, TEGDMA, silica-zirconia filler (260 nm)	Supra-nano filled (79 wt%, 68 vol%)	Tokuyama Dental, Tokyo, Japan
FS	Filtek Suprem Ultra (Shade; A2: N870378)	bis-GMA, UDMA, TEGDMA, bis-EMA, PEGDMA, zirconia/silica clusters (0.6-10 μm) silica (20 nm silica filler), zirconia (4-11 nm)	Nano filled (78.5 wt%, 63.3 vol%)	3M Oral Care, St. Paul, MN, USA
TE	Tetric EvoCeram (Shade; A2: T21387)	bis-GMA, UDMA, bis-EMA barium glass, ytterbium trifluoride, mixed oxide and pre-polymer (range: 40 nm-3 μm, average: 550 nm)	Nano hybrid (75-76 wt%, 53-55 vol%)	Ivoclar Vivaden, Schaan, Lichtenshtein
Code	**Finishing Bur**	**Model**	**Manufacturer**	
SFD	Super fine grit diamond bur	SF102R (ISO#017, particle size less than 25 μm)	Shofu, Kyoto, Japan	
TCB	Tungsten carbide bur	FG7714 (ISO#014, 12 blades)	Kerr, Orange, CA, USA	
Code	**Polishing System**	**Model**	**Manufacturer**	
CMP	Compomaster (one step system)	One step diamond polisher (6 μm) silicone base (25%), diamond |particles (75%)	Shofu	
SSD	Super-Snap (multi step system)	SSD G: Fine, green: σ12-mm disk; 20-μm aluminium oxide SSD R: Superfine, red: σ12-mm disk; 7-μm aluminium oxide	Shofu	

Abbreviations: UDMA, urethane dimethacrylate, TEGDMA: triethyleneglycol dimethacrylate; bis-GMA, 2,2-bis[4-(2-hydroxy-3-methacryloyloxypropoxy) phenyl) propane; bis-EMA, bisphenol A polyethylene glycol diether dimethacrylate; PEGDMA: poly ethylene glycol diether dimethacrylate.

were polished using the multistep polishing system comprising aluminum oxide-impregnated disks (SSD; Super-Snap Rainbow Technique Kit, Shofu). All the polishing procedures were performed using a slow-speed handpiece (TorqTech CA-DC; J. Morita Mfg.) at 5,000 rpm and contact pressure of 1.0 N, which was monitored with a digital balance (AT200; Mettler-Toledo, Greifensee, Switzerland) underneath the specimen. All specimens were finished and polished by a single operator to reduce variability between samples.

The final groups of specimens from each type of composite were as follows: ground with 320-grit SiC paper (BAS); finished with SFD (SFD); finished with TCB (TCB); SFD polished with CMP (SFD+CMP); TCB polished with CMP (TCB+CMP); SFD polished with SSD (SFD+SSD); and TCB polished with SSD (TCB+SSD).

Measurement of Surface Area Roughness

Before the *Sa* measurements, the finished and polished specimens were cleaned with distilled water in an ultrasonic bath (Quantrex 301; L&R Ultrasonics, Kearny, NJ, USA) for 3 minutes and dried in oil-free air. The surfaces of all the specimens were observed using a three-dimensional laser scanning microscope (LSM, VK-8700; Keyence, Osaka, Japan). The spectral maximum of the excitation light was observed to be at 658 nm; the intensity of the excitation light and the amplification of the photomultiplier were kept constant during the observation period. Profilometric measurements were conducted in a region (1.0 mm ×

1.0 mm) at the center of the specimen. The *Sa* value was obtained using the built-in computer software (VK Analyzer; Keyence) connected to the LSM. Three measurements were taken, and the means were then determined for each group.

Measurement of Surface Gloss

The GU of each group was measured using a gloss meter (GM-26D; Murakami Color Research Laboratory, Tokyo, Japan) after the *Sa* measurements were obtained. The gloss meter was calibrated with a blackboard of known gloss value. Subsequently, the GU measurements were taken with an incident angle of 60 degrees, and the values for each group were determined.

Measurement of Surface Free Energy (SFE)

The contact angles of the specimens were measured in order to evaluate the surface characteristics. The contact angles of the three test liquids with known SFE parameters, 1-bromonaphthalene, di-iodomethane, and distilled water were measured using a contact angle meter (Drop Master DM500; Kyowa Interface Science, Saitama, Japan) with a built-in charge-coupled device camera.[12] The equilibrium contact angle (θ) of each test liquid on the specimens was then measured using the sessile-drop method at room temperature (23±1°C). Sessile liquid drops (1.0 μL) were dispensed with a micropipette, and the surface characteristics were calculated based on the fundamental concepts of wetting. The Young-Dupré equation has associated contact angle to the work of adhesion for a solid (S) and liquid (L) that are in contact (W_{SL}), the interfacial free energy between the S and the L (γ_{SL}), and the free energies of the L and S (γ_L and γ_S, respectively) and is expressed as follows:

$$W_{SL} = \gamma_L + \gamma_S - \gamma_{SL} = \gamma_L (1 + \cos\theta).$$

An extension of the Fowkes equation following the Kitazaki-Hata approach[23] yields the following equations:

$$\gamma_{SL} = \gamma_L + \gamma_S - 2 (\gamma_L^d \gamma_S^d)^{1/2} - 2 (\gamma_L^p \gamma_S^p)^{1/2} - 2 (\gamma_L^h \gamma_S^h)^{1/2},$$

$$\gamma_L = \gamma_L^d + \gamma_L^p + \gamma_L^h, \gamma_S = \gamma_S^d + \gamma_S^p + \gamma_S^h,$$

where, γ^d, γ^p, and γ^h are the components of the SFE (γ) arising from the dispersion force, the polar (permanent and induced) force, and the hydrogen-bonding force, respectively. The θ values were determined for the three test liquids, and the surface-energy parameters of the treated resin composites were obtained using the above equations using add-on software (FAMAS, Kyowa Interface Science).

SEM Observations

To visualize the morphological features of the fillers in the resin composites, the polymerized specimens were polished using abrasive disks and a series of diamond pastes (DP-Paste; Struers, Ballerup, Denmark) down to a particle size of 0.25 μm. The mirror-polished surfaces were subjected to argon-ion beam etching (IIS-200ER; Elionix, Tokyo, Japan) for 40 seconds, with the ion beam directed perpendicular to the polished surface (accelerating voltage = 1 kV, ion current density = 0.4 mA/cm^2). The surfaces were then coated with a thin film of Au in a vacuum evaporator (Quick Coater Type SC-701; Sanyu Denchi, Tokyo, Japan). Images were obtained using an SEM (FE-8000; Elionix, Vienna, Austria) at an operating voltage of 10 kV at magnifications of 5,000× and 30,000×.

In order to understand the surface texture of the finishing and polishing instruments before use, Au-coated surfaces were observed by SEM at magnifications of 50× and 1,000×. Furthermore, SEM observations of representative specimens from the three resin composites were performed after the different finishing and polishing procedures. The coated surfaces were visualized by SEM at a magnification of 2,500×.

Statistical Analysis

A power analysis has indicated that at least 10 samples for flexural properties and eight samples for surface properties and SFE measurements were needed. Thus, this study was initially performed with 12 specimens for flexural property testing and 10 for other measurements. After gathering the data, *post hoc* power tests were performed using two statistical software systems (G Power calculator and SigmaPlot ver. 13.0; Systat Software, Inc, Chicago, IL, USA).

After confirming that the distribution was normal using the Kolmogorov-Smirnov test, data from each experiment were subjected to the analysis of variance (ANOVA) test; this was followed by the Tukey honest significant difference test at a significance level of 0.05. Significant differences in flexural properties were observed using the one-way ANOVA test, whereas differences in surface roughness, surface gloss, and total SFE were assessed using the two-way ANOVA test; the type of resin composite and the polishing method were used as factors for the two-way ANOVA. The statistical analyses were carried out using a commercially available statistical software program (SigmaPlot ver. 13.0).

The Pearson product-moment correlation coefficient was also used to perform pairwise comparisons, in

Table 2: *Flexural Properties of the Tested Resin Composites*[a,b]

	Flexural Strength; σ_F (MPa)	Elastic modulus; *E* (GPa)	Resilience; *R* (MJ/mm³)
OM	116.6 (4.8) c	6.8 (0.6) c	1.01 (0.11) a
FS	142.3 (5.8) a	13.2 (0.6) a	0.78 (0.06) b
TE	125.3 (5.2) b	9.3 (0.8) b	0.85 (0.11) b

Abbreviations: FS, Filtek Supreme Ultra; OM, Omnichroma; TE, Tetric EvoCeram.

[a]*Values in parentheses indicate standard deviation.*

[b]*Same small case letter in vertical columns indicates no difference at 5% significance level.*

order to understand the relationships between the tested parameters of the surface properties (SigmaPlot version 13.0, Systat).

RESULTS

Flexural Properties

The flexural properties of the resin composites are presented in Table 2. The average σ_F ranged from 116.6 to 142.3 MPa in the following order with significant differences between each value: FS > TE > OM. The average *E* ranged from 6.8 to 13.2 GPa in the following order with significant differences between each value: FS > TE > OM. FS showed significantly higher *E* and σ_F values compared to the other resin composites. The average *R* ranged from 0.78 to 1.01 MJ/mm³ in the following order: OM > TE > FS. Although no significant difference was determined between FS and TE, OM showed a significantly higher *R* than the other resin composites, in contrast to σ_F and *E*.

Surface Area Roughness

The influence of different finishing and polishing methods on the *Sa* values is shown in Table 3. A two-way ANOVA revealed that the finishing and polishing methods and the type of resin composite can significantly affect the *Sa* values ($p<0.001$). The two-way interaction between these two factors was also found to be significant ($p<0.001$). The groups finished with SFD showed significantly higher *Sa* values when compared with the other groups, regardless of the type of resin composite used. On the other hand, the TCB+SSD group showed the lowest *Sa* values compared to the other groups, and significant differences in FS and TE were observed between the TCB+SSD group and the other groups. In addition, most groups polished with SSD showed significantly lower *Sa* values compared to the groups polished with CMP, regardless of the type of finishing used (SFD or TCB).

Among the tested resin composites, no significant differences were observed between the BAS and TCB groups. However, the *Sa* values of the OM groups polished with CMP and SSD were found to be significantly lower than those of the other resin composites, regardless of the finishing method.

Gloss

The effects of the different finishing and polishing methods on the GU values are shown in Table 4. The two-way ANOVA test revealed that both factors, ie, finishing and polishing methods and the type of resin

Table 3: *Influence of Finishing and Polishing Methods on Surface Area Roughness (Sa, μm)*[a,b]

	BAS	SFD	TCB	SFD+CMP	TCB+CMP	SFD+SSD	TCB+SSD
OM	1.32 (0.02) aB	1.51 (0.02) bA	1.05 (0.02) aC	0.92 (0.03) cD	0.85 (0.01) cE	0.78 (0.02) cF	0.78 (0.02) cF
FS	1.31 (0.02) aB	1.60 (0.05) aA	1.05 (0.02) aC	1.00 (0.02) bD	0.99 (0.04) bD	0.93 (0.04) bE	0.88 (0.02) bF
TE	1.30 (0.01) aB	1.46 (0.03) cA	1.03 (0.02) aCD	1.07 (0.05) aC	1.01 (0.03) aD	1.00 (0.02) aD	0.85 (0.04) aE

Abbreviations: BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; OM,Omnichroma; SFD, superfine grit diamond bur; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram.

[a]*Values in parentheses indicate standard deviation.*

[b]*Same small case letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.*

Table 4: *Influence of Finishing and Polishing Methods on Surface Gloss (GU)*[a,b]

	BAS	SFD	TCB	SFD+CMP	TCB+CMP	SFD+SSD	TCB+SSD
OM	3.7 (0.2) bF	1.8 (0.1) cG	22.9 (0.6) aE	34.1 (1.0) bD	44.3 (0.4) bC	50.6 (1.0) aB	53.3 (1.2) aA
FS	7.4 (0.2) aF	2.7 (0.1) aG	12.4 (0.2) bE	53.7 (0.6) aB	65.2 (0.2) aA	31.8 (0.3) bD	40.7 (0.5) cC
TE	3.4 (0.1) cF	2.0 (0.1) bG	22.6 (0.2) aE	35.5 (0.4) bC	44.1 (0.8) bB	32.8 (0.8) bD	48.5 (0.3) bA

Abbreviations: BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; OM, Omnichroma; SFD, superfine grit diamond bur; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram.

[a]*Values in parentheses indicate standard deviation.*

[b]*Same small case letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.*

composite used, have significantly affected the GU ($p<0.001$). In addition, a significant two-way interaction between these two factors was observed ($p<0.001$). The GU values of the BAS, SFD, and TCB groups were significantly lower than those of the groups polished with CMP and SSD. Furthermore, the specimens in the groups finished with TCB had significantly higher GU values compared to those finished with SFD. In addition, the specimens finished with TCB demonstrated significantly higher GU values when compared with those finished with SFD. The GU values also appeared to be dependent on the material and the finishing method used. The OM specimens polished with SSD showed significantly higher GU values than those polished with CMP. However, the FS specimens that had been polished with SSD showed significantly lower GU values compared to those polished with CMP, regardless of the finishing method. On the other hand, the TE specimens polished with SSD showed a different trend in their GU values when compared with the specimens finished with SFD and TCB.

Surface Free Energy

The effects of the different finishing and polishing methods on the SFE values are shown in Table 5 and Figure 1. A two-way ANOVA revealed that the finishing and polishing method, as well as the type of resin composite used, significantly influenced the γ_S value ($p<0.001$). The two-way interaction between the factors was also found to be significant ($p<0.001$).

The specimens in most of the groups polished with SSD showed significantly higher γ_S values compared to those in the other groups. The polished OM specimens showed significantly higher γ_S values compared to those in the BAS and other finished groups. In the case of the FS specimens, although the specimens in the TCB + SSD group presented with significantly higher γ_S value than those in the other groups, no significant differences were observed among the specimens in the other groups. The γ_S values of the TE specimens polished with CMP were found to be lower than those in the other groups. FS tended to have higher γ_S values when compared with the other resin composites, regardless of the finishing and polishing methods.

With regard to each component of the γ_S (Figure 1), although the dispersion force (γ_S^d) was constant at approximately 40 $mN \cdot m^{-1}$ in all the groups, variations in the polar force (γ_S^p) and hydrogen-bonding force (γ_S^h) were observed among the groups. However, all three resin composites tended to have higher γ_S^p values when

Table 5: *Influence of Finishing and Polishing Methods on Total SFE (γ_S)*[a,b]

	BAS	SFD	TCB	SFD+CMP	TCB+CMP	SFD+SSD	TCB+SSD
OM	45.2 (2.0) bC	43.5 (1.9) bD	44.6 (2.2) cCD	48.4 (1.8) bB	48.2 (0.9) bB	50.8 (1.2) aA	50.6 (1.2) bA
FS	51.2 (1.8) aB	51.8 (1.5) aB	51.0 (0.9) aB	51.2 (1.1) aB	51.7 (1.5) aB	51.4 (1.2) aB	53.9 (2.2) aA
TE	49.4 (1.4) aBC	50.5 (1.6) aAB	48.2 (1.4) bCD	47.0 (1.5) bD	46.6 (1.2) cD	51.8 (1.0) aA	51.4 (1.6) bA

Abbreviations: BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; OM, Omnichroma; SFD, superfine grit diamond bur; SFE, surface-free energy; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram.

[a]*Values in parentheses indicate standard deviation.*

[b]*Same small case letter in vertical columns indicates no difference at 5% significance level. Same capital letter in horizontal rows indicates no difference at 5% significance level.*

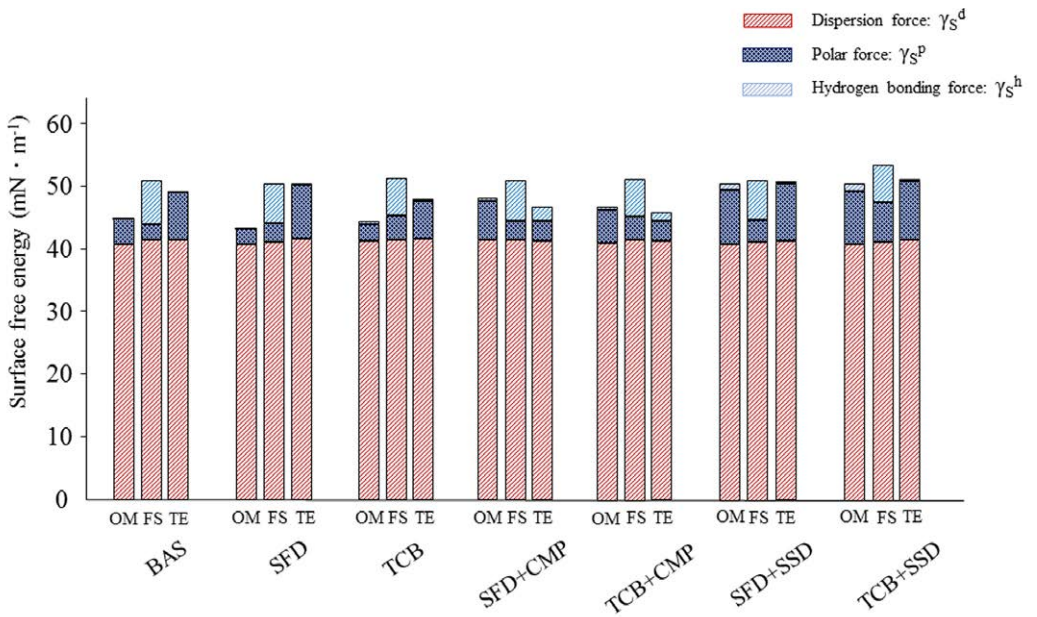

Figure 1. *The total SFE (γ_S) values and the three corresponding parameters of the resin composites. Abbreviations: γ_S, total surface free energy; BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; GU, surface gloss; OM, Omnichroma; SFD, superfine grit diamond bur; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram.*

polished with SSD when compared with the other finishing and polishing methods. The FS specimens had higher γ_S^h components than the other resin composites, regardless of the finishing and polishing methods.

Interrelations Between the Tested Parameters of the Surface Properties

The Pearson product-moment correlation coefficient (r) and p values for the relations between the tested parameters of the surface properties are presented in Table 6. Extremely strong negative correlations between *Sa* and GU in the combined data from the three resin composites and each resin composite and between *Sa* and γ_S in the OM specimens were observed; GU showed a strong positive correlation with γ_S in the same material, and those correlations were revealed to be individually statistically significant. However, the other comparisons showed weak correlations or no correlations.

SEM Observations

SEM images of the mirror-polished surfaces after argon-ion etching are illustrated in Figures 2 through 4. The shapes, sizes, and distributions of the inorganic fillers are found to be resin composite dependent. OM consisted of nanosized spherical fillers (approximately 0.25 μm) and round pre-polymerized fillers that employ the same nanosized spherical fillers (Figure 2). FS consisted of spheroidal aggregates (0.5-5.0 μm) of nanosized filler particles (Figure 3), whereas TE consisted of irregular fillers (0.5-2.0 μm) made up of nanosized filler particles that were packed into pre-polymerized fillers at a high density (Figure 4).

Representative SEM images of the surfaces of the instruments are shown in Figure 5. SFD consisted of embedded irregular diamond particles that were less than 20 μm in size. On the other hand, TCB consisted of sharp uniform blades. The one-step polishing instrument CMP consisted of impregnated irregular diamond particles, and the interfaces between the particles and matrix appeared to be loose. In the case of the multiple polishing system, SSD, the sizes of the aluminum oxide particles were found to be varied in the different disks (SSD G and SSD R). The particles in SSD R were tightly packed when compared to those in CMP and SSD G.

Representative SEM images of the resin composite surfaces after the different finishing and polishing methods are shown in Figures 6-8. All the resin composites exhibited smoother surfaces after finishing with TCB when compared to those finished with SFD. For FS and TE, scratches and plucked-out fillers were observed following polishing with SFD. In particular, plucked-out aggregated fillers were seen in the FS specimens, whereas large glass fillers were observed in the TE specimens.

When comparing the different polishing methods (CMP and SSD), smoother surfaces were observed in the

Table 6: Relationships Between the Parameters of Surface Properties			
		GU	γ_s
Combined data of three resin composites			
Sa	*r*	-0.847	-0.274
	p-value	<0.001	0.230
GU	*r*		0.318
	p-value		0.160
OM			
Sa	*r*	-0.972	-0.897
	p-value	<0.001	0.006
GU	*r*		0.930
	p-value		0.002
FS			
Sa	*r*	-0.713	-0.265
	p-value	0.072	0.566
GU	*r*		0.222
	p-value		0.632
TE			
Sa	*r*	-0.921	0.026
	p-value	0.003	0.956
GU	*r*		-0.145
	p-value		0.756
Abbreviations: γ_S, total surface free energy; BAS, baseline; CMP, diamond particle; FS, Filtek Supreme Ultra; GU, surface gloss; OM, Omnichroma; r*, correlation coefficient; Sa, surface roughness; SFD, superfine grit diamond bur; SSD, aluminum oxide-impregnated disks; TCB, tungsten carbide bur; TE, Tetric EvoCeram*			

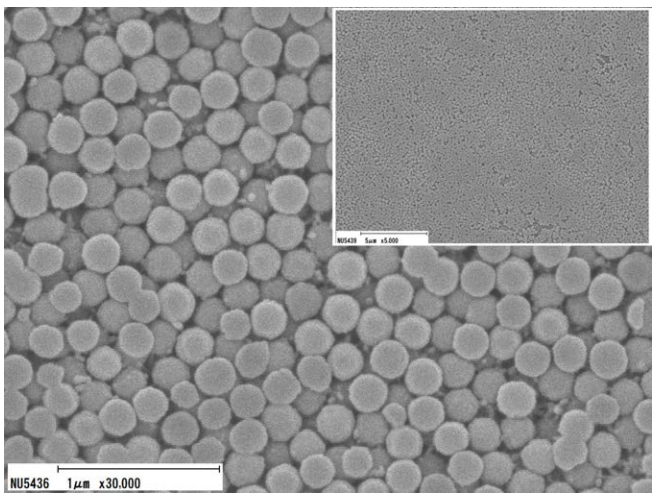

Figure 2. *SEM images of resin composite surfaces after argon-ion etching Omnichroma (OM) – 5000× and 30,000×. Abbreviation: SEM, scanning electron microscopy.*

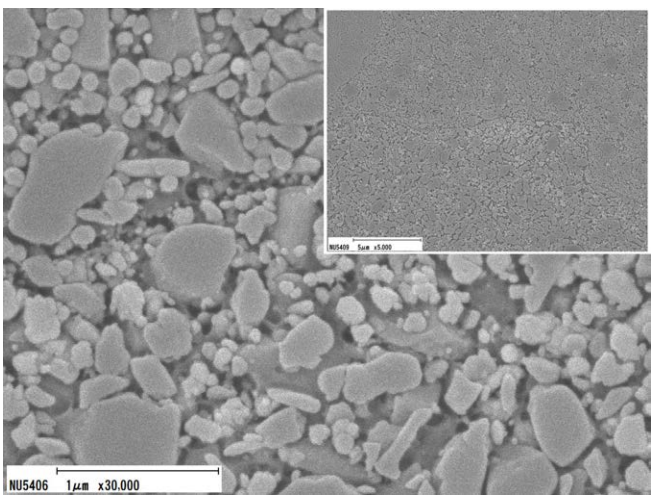

Figure 3. *SEM images of resin composite surfaces after argon-ion etching. Filtek Supreme Ultra (FS) – 5000× and 30,000×. Abbreviation: SEM, scanning electron microscopy.*

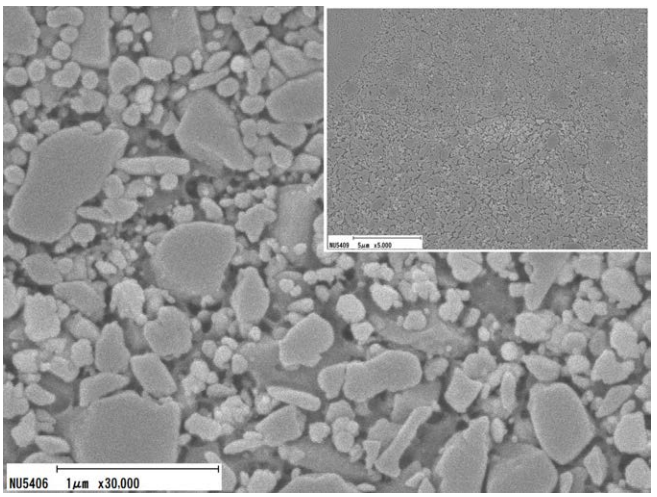

Figure 4. *SEM images of resin composite surfaces after argon-ion etching Tetric EvoCeram (TE) – 5000× and 30,000×. Abbreviation: SEM, scanning electron microscopy.*

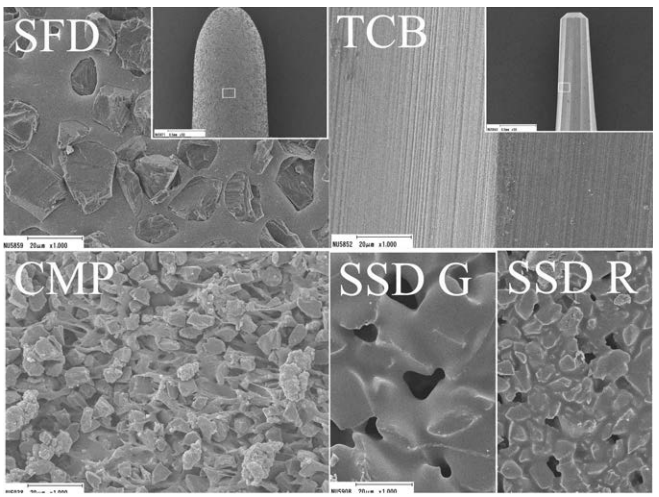

Figure 5. *SEM images of resin composite surfaces after argon-ion etching. Representative SEM images of the instruments' surfaces. CMP, One-step diamond polisher, Compomaster (1,000x); SEM, scanning electron microscopy; SFD, Super fine grit diamond bur (50x and 1,000x); SSDG, Multistep polishing system, Super-Snap fine green (1,000x); SSDR, Multistep polishing system, Super-Snap super fine red (1,000x); TCB, Tungsten carbide bur (50x and 1,000x). Abbreviation: SEM, scanning electron microscopy.*

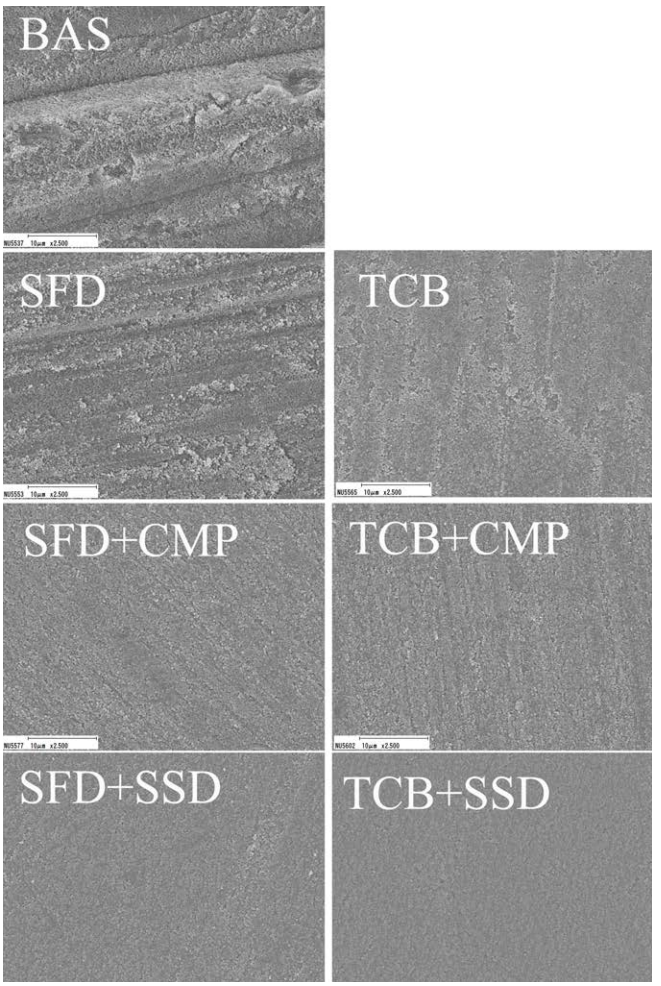

Figure 6. *Representative SEM images of OM after different finishing and polishing methods. BAS, Ground with SiC #320 (2,500×); SEM, scanning electron microscopy; SFD, Finished with Super-fine grit diamond (2,500×); SFD+CMP, Polished with Compomaster after finishing with Super-fine grit diamond bur (2,500×); SFD+SSD, Polished with Super-Snap after finishing with Super-fine grit diamond bur (2,500×); TCB, Finished with Tungsten carbide bur (2,500×); TCB+CMP, Polished with Compomaster after finishing with Tungsten carbide bur (2,500×); TCB+SSD, Polished with Super-Snap after finishing with Tungsten carbide bur (2,500×). Abbreviation: SEM, scanning electron microscopy.*

SSD groups in the case of the OM and FS specimens, regardless of the finishing method. On the contrary, in the case of the TE specimens, there exists no difference in surface smoothness between the SSD and CMP groups.

DISCUSSION

Understanding the various properties of resin composites before clinical use will aid in selecting the optimum resin composite, which will in turn lead to ideal outcomes in the intraoral environment.[7,8] In this study, the flexural and surface properties of the structural colored resin composite OM were investigated and compared with those of the conventional resin composites FS and TE.

When considering the longevity of resin composite restorations in intraoral conditions, fracture-related material properties are important. Flexural strength testing is a well established standardized method, and it is preferred as a way to screen the mechanical properties of materials due to ease of testing. These values are helpful in comparing materials under controlled conditions and also provide some help

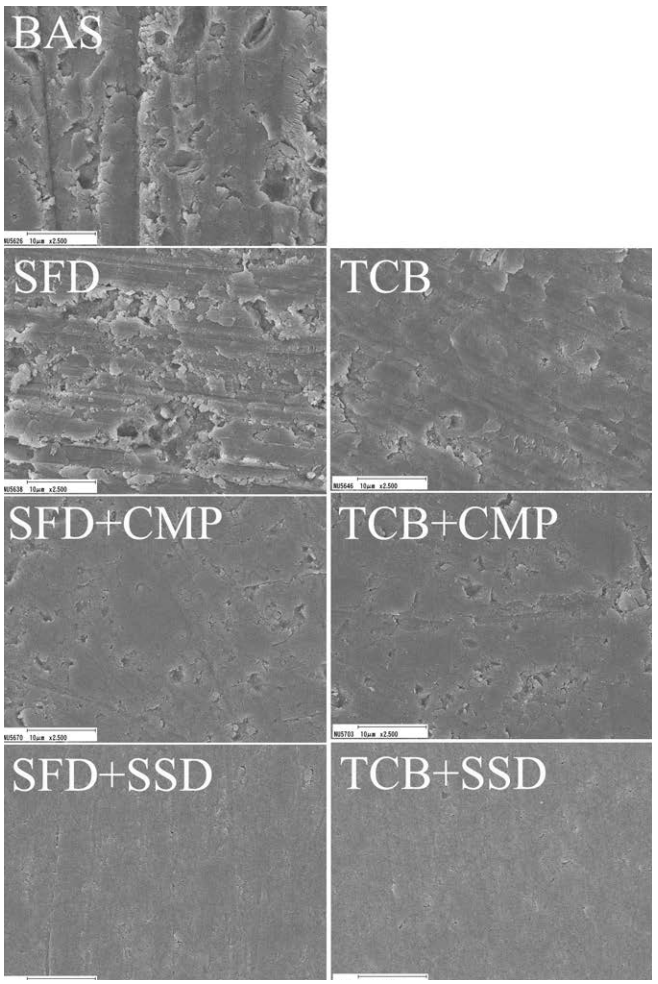

Figure 7. *Representative SEM images of FS after different finishing and polishing methods. BAS, Ground with SiC #320 (2,500×); SEM, scanning electron microscopy; SFD, Finished with Super-fine grit diamond bur (2,500×); SFD+CMP, Polished with Compomaster after finishing with Super-fine grit diamond bur (2,500×); SFD+SSD, Polished with Super-Snap after finishing with Super-fine grit diamond bur (2,500×); TCB, Finished with Tungsten carbide bur (2,500×); TCB+CMP, Polished with Compomaster after finishing with Tungsten carbide bur (2,500×); TCB+SSD, Polished with Super-Snap after finishing with Tungsten carbide bur (2,500×). Abbreviation: SEM, scanning electron microscopy.*

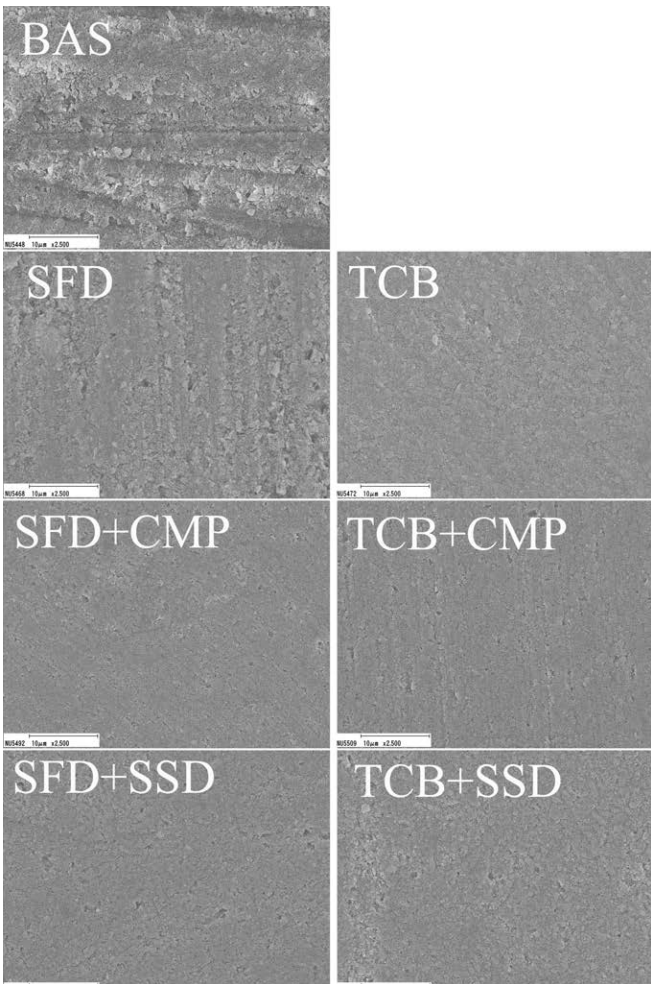

Figure 8. *Representative SEM images of TE after different finishing and polishing methods. BAS, Ground with SiC #320 (2,500×); SEM, scanning electron microscopy; SFD, Finished with Super-fine grit diamond bur (2,500×); SFD+CMP, Polished with Compomaster after finishing with Super-fine grit diamond bur (2,500×); SFD+SSD, Polished with Super-Snap after finishing with Super-fine grit diamond bur (2,500×); TCB, Finished with Tungsten carbide bur (2,500×); TCB+CMP, Polished with Compomaster after finishing with Tungsten carbide bur (2,500×); TCB+SSD, Polished with Super-Snap after finishing with Tungsten carbide bur (2,500×). Abbreviation: SEM, scanning electron microscopy.*

in predicting restoration longevity. The mechanical properties of resin composites are influenced by the resin monomers, filler characteristics, and surface treatment of the fillers. The findings of this study were found to be consistent with the results of the previous studies, which investigated the flexural properties of nanohybrid and nanofilled resin composites, including the resin composites used in this study.[24,25] FS showed significantly higher σ_F and E values compared to TE in the current study. Thus, it can be speculated that the fine nanosized spherical fillers and the aggregated fillers with a wide range of sizes in FS might contribute to higher fracture resistance.

In general, materials with high flexural strength have high elastic moduli.[26,27] OM presented with significantly lower E values compared to the other materials despite having a higher filler content. Of the monomers used in the tested composites, 2,2-bis[4-(2-hydroxy-3-methacryloyloxypropoxy)phenyl) propane (bis-GMA) has a relatively higher molecular weight and lower mobility compared to urethane dimethacrylate (UDMA) and triethyleneglycol dimethacrylate (TEGDMA).

Izabela and others,[28] who examined the mechanical properties of three common homopolymers, have reported that UDMA had a lower *E* than bis-GMA and TEGDMA. UDMA is the resin monomer used in OM. However, although the type of resin monomer used can influence the flexural properties of a resin composite, it is difficult to identify the exact resin monomer and its effects on σ_F and *E* due to the various types present in resin composites; moreover, the interactions between resin monomers and inorganic fillers may differ between composites. OM has been known to consist of uniformly sized spherical fillers with constant interparticle spacing. FS consists of non-aggregated silica (20 nm) and zirconia fillers (4 to 11 nm), whereas OM consists of silica-zirconia fillers (260 nm). The fillers in OM were found to have greater interparticle spaces (Figures 2 and 3) than those in FS. Therefore, crack propagation in OM tended to be simple, leading to lower fracture resistance. On the other hand, *R* is thought to be the ability of a material to absorb energy when it is elastically deformed under external stress without failing.[26] OM showed a significantly higher *R* value compared to the other resin composites. This may be attributed to the presence of UDMA, which acts as a very flexible backbone with weak hydrogen-bonding due to the urethane groups. Therefore, the first null hypothesis, which indicates that the flexural properties of OM would not differ from those of other resin composites, was rejected.

The surface characteristics of resin composites, in addition to the mechanical properties, must be understood to predict their longevity in the intraoral environment, because the surfaces of restorations are directly subjected to various degradation factors.[10,11] From the results of this study, the two factors, ie, finishing and polishing procedure and type of resin composite used, have significantly influenced the *Sa* values. In particular, the groups finished with SFD showed significantly higher *Sa* values compared to those finished with TCB, regardless of the type of resin composite. This result was in line with a previous study that investigated the surface roughness of bulk-fill resin composites after different finishing and polishing procedures.[12] This finding may be explained by the different surface textures of the finishing instruments (Figure 5) resulting in different finishing mechanisms. The tungsten carbide burs cut away the surface, whereas diamond burs grind the surface with many abrasive diamond particles.[29,30] SEM observations clearly showed that some filler particles were plucked from the surfaces in the case of SFD, whereas in the case of TCB polishing, the filler particles remained embedded in the surface, resulting in a smoother surface (Figures 6 and 7). Furthermore, the finishing methods have significantly affected the polished groups, because most of the specimens in the TCB group showed lower *Sa* values compared to those in the SFD group, regardless of whether CMP or SSD was used.

The multiple-step polishing system (SSD) created smoother surfaces compared with the one-step polishing system (CMP; Figures 6 through 8). This might be attributed to the distribution (Figure 5) and the hardness of the particles in the different polishing instruments. Watanabe and others[31] indicated that, although the one-step polishing system has the capacity to polish resin composites as effectively as multistep polishing systems, the smoothest surface was obtained with multistep polishing systems. Among the resin composites, OM has showed significantly lower *Sa* values compared to the other resin composites for all the polishing methods. It can be inferred that the superior polishability of OM is probably due to the uniform nanoscale spherical fillers and the constant interspaces between them.

The surface gloss of restorations has been considered an important parameter for esthetics.[32] Gloss is defined based on the degree of specular reflection of light.[33] The finishing and polishing methods and type of resin composite used have significantly affected the GU in the current study. The GU obtained after polishing is known to be dependent on the type of material and the finishing method used. Although the OM specimens polished with SSD showed significantly higher GU values compared to those polished with CMP, the opposite findings were observed in the FS specimens, regardless of the finishing method used. Cazzaniga and others[34] obtained similar results wherein FS specimens polished with aluminum oxide disks showed lower surface roughness compared to those polished with one-step rubber points; however, a significantly higher surface gloss was obtained when polished with the one-step rubber points. In general, surface roughness and gloss are thought to have a negative correlation.[35,36] Nonetheless, a smoother surface is not necessary to obtain a high surface gloss, and the relationship depends on the polishing procedures and materials used.[34] Although 40 to 60 GU was identified as the typically desired gloss in an American Dental Association professional product review,[37] Cook and Thomas[38] reported that a finish and polish below 60 GU was generally considered as poor; the acceptable values lie between 60 and 70 GU. However, a systematic review on surface gloss reported that few investigations showed a gloss of over 60 GU, even when the final polishing was performed.[32] Therefore, if the clinically acceptable GU is assumed to be 40 to 60 GU, SSD groups for OM and CMP groups for FS may be acceptable.

The SFEs were determined to understand the surface changes wrought by the different finishing and polishing methods from the perspective of surface chemistry. The finishing and polishing methods and the type of resin composite used significantly influenced the γ_S in this study. Therefore, the second null hypothesis, which implies that the surface properties of OM would not be affected by the finishing and polishing methods and would not differ from the other resin composites, was rejected. For all the resin composites, the groups polished with SSD showed significantly higher γ_S values when compared with the other groups. Fundamentally, the wettability of a substance increases with the increase in the γ_S value.[39,40] In composite resins, inorganic fillers are hydrophilic, whereas the resin matrix is hydrophobic.[12] The increase in the γ_S values in the SSD groups may be attributed to the high level of inorganic filler exposure on the surface due to the polishing method. A flexible disk coated with aluminum oxide might be able to cut the filler particles effectively, leaving parts of the filler particles exposed at the surface. This process produces uniform surface conditions without the plucking of the fillers, improving its resistance to various degradation factors.

γ_S^h represents the water and hydroxyl components of the substrate, whereas γ_S^p is related to the electronic and metallic interactions and the dipolar interactions.[39,40] Although the γ_S^p and γ_S^h values in each group showed wide variations, some trends were observed between the materials or the finishing and polishing methods. FS had a higher number of γ_S^h components than the other resin composites in all the groups. This trend is likely brought about by the different surface chemistries between the exposed fillers and the resin matrix. The reasons why FS showed higher γ_S^h might be related to the relatively higher vol% of inorganic filler components and the somewhat larger nanofiller clusters, in addition to the presence of relatively hydrophilic resin monomers. In a previous study, which investigated the water sorption of common homopolymers, the descending order of water sorption was reported as TEGDMA > bis-GMA > UDMA.[41] The study suggested that these differences could be attributed to the presence of hydrophilic ether linkages in TEGDMA, hydroxyl groups in bis-GMA, and urethane linkages in UDMA. Although the parts of resin monomers related to hydrophilicity might increase the γ_S^h, it is difficult to determine the details of the interactions between γ_S^p or γ_S^h and the inorganic fillers or resin matrix due to the complexity of the resin composites.

Regarding the interrelations between the tested parameters of the surface properties, extremely strong correlations were observed between *Sa* and GU in all the resin composites, as reported previously.[35,36] Therefore, in order to obtain an esthetic and smooth surface on the restoration, it is important to conduct appropriate finishing and polishing procedures. On the other hand, extremely strong correlations were observed between *Sa* and γ_S and GU and γ_S in the OM specimens only, indicating that finishing and polishing methods may have a larger impact on the surface properties of OM when compared to the other resin composites.

Structural colors depend on the refractive index distribution and the differences in the refractive indices of the resin matrix and the inorganic filler.[17,19] Although appropriate finishing and polishing procedures may be necessary to generate a structural color in OM, further studies are needed to determine the influence of the different finishing and polishing procedures on color matching.

CONCLUSION

Although the structural colored resin composite OM showed significantly lower σ_F and E values, it had a significantly higher R compared to the other resin composites. These results suggest that cavity status should be taken into consideration when using OM in clinical situations. The finishing and polishing methods along with the type of resin composite used have significantly affected the surface properties of the resin composite, as measured by the *Sa*, GU, and SFE values. SEM observations demonstrated that the shapes, sizes, and distributions of the fillers varied among the resin composite, and different surface appearances were observed with the different finishing and polishing methods used. In the case of the OM specimens, the use of the multiple polishing system (SSD) after finishing with a TCB may improve its surface properties when compared with the other finishing and polishing methods.

Acknowledgements

This work was supported in part by Grants-in-Aid for Scientific Research (grant nos. 19K10158 and No. 19K10159) from the Japan Society for the Promotion of Science. This project was also supported in part by the Sato Fund, Uemura Yasuo Haruko Fund, and by a grant from the Dental Research Center of the Nihon University School of Dentistry, Japan.

Conflict of Interest

The authors have no financial interest in any of the companies or products mentioned in this article.

(Accepted 13 September 2020)

REFERENCES

1. Lee YK, Yu B, Lee S-H, Cho M-S, Lee C-Y, & Lim H-N (2010) Shade compatibility of esthetic restorative materials–A review *Dental Materials* **26(12)** 1119-1126. https://doi: 10.1016/j.dental.2010.08.004
2. Khashayar G, Dozic A, Kleverlaan CJ, Feilzer AJ, & Roeters J (2014) The influence of varying layer thicknesses on the color predictability of two different composite layering concepts *Dental Materials* **30(5)** 493-498. https://doi: 10.1016/j.dental.2014.02.002
3. Miotti LL, Santos IS, Nicoloso GF, Pozzobon RT, Susin AH, & Durand LB (2017) The use of resin composite layering technique to mask discoloured background: A CIELAB/CIEDE2000 analysis *Operative Dentistry* **42(2)** 165-174. https://doi:10.2341/15-368-L
4. LeSage B (2014) Direct composite resin layering techniques for creating lifelike CAD/CAM-fabricated composite resin veneers and crowns *Journal of Prosthetic Dentistry* **112(1)** 5-8. https://doi: 10.1016/j.prosdent.2014.01.014
5. Jefferies SR (2007) Abrasive finishing and polishing in restorative dentistry; A state-of-the-art review *Dental Clinics of North America* **52(2)** 379-397. https://doi: 10.1016/j.cden.2006.12.002
6. Endo T, Finger WJ, Kanehira M, Utterodt A, & Komatsu M (2010) Surface texture and roughness of polished nanofill and nanohybrid resin composites *Dental Materials Journal* **29(2)** 213-223. https://doi: 10.4012/dmj.2009-019
7. Ferracane JL (2011) Resin composite-state of the art *Dental Materials* **27(1)** 29-38. https://doi: 10.1016/j.dental.2010.10.020
8. Heintze SD, Ilie N, Hickel R, Reis A, Loguercio A, & Rousson V (2017) Laboratory mechanical parameters of composite resins and their relation to fractures and wear in clinical trials-A systematic review *Dental Materials* **33(3)** e101–e114. https://doi: 10.1016/j.dental.2016.11.013
9. Imai A, Takamizawa T, Sugimura R, Tsujimoto A, Ishii R, Kawazu M, Saito T, & Miyazaki M (2019) Interrelation among the handling, mechanical, and wear properties of the newly developed flowable resin composites *Journal of the Mechanical Behavior of Biomedical Materials* **89** 72-80. https://doi: 10.1016/j.jmbbm.2018.09.019
10. Bollen CM, Lambrechts P, & Quirynen M (1997) Comparison of surface roughness of oral hard materials to the threshold surface roughness for bacteria plaque retention; a review of the literature *Dental Materials* **13(4)** 258-269. https://doi: 10.1016/s0109-5641(97)80038-3
11. Reis AF, Giannini M, Lovadino JR & Ambrosano GM (2003) Effects of various finishing systems on the surface roughness and staining susceptibility of packable composite resins, *Dental Materials* **19(1)** 12-18. https://doi: 10.1016/s0109-5641(02)00014-3
12. Ishii R, Takamizawa T, Tsujimoto A, Suzuki S, Imai A, Barkmeier WW, Latta MA, & Miyazaki M (2020) Effects of finishing and polishing methods on the surface roughness and surface free energy of bulk-fill resin composites *Operative Dentistry* **45(2)** E91–E104. https://doi: 10.2341/18-246-L
13. Zhao Y, Zhao Y, Hu S, Lv J, Ying Y, Gervinskas G, & Si G (2017) Artificial structural color pixels: A review *Materials (Basel)* **10(8)** 944. https://doi: 10.3390/ma10080944
14. Dumanli AG & Savin T (2016) Recent advances in the biomimicry of structural colours *Chemical Society Reviews* **45(24)** 6698-6724. https://doi: 10.1039/c6cs00129g
15. Chen J, Liu P, Du X, & Xie Z (2018) Clickable colloidal photonic crystals for structural color pattern *Langmuir* **34(44)** 13219-13224. https://doi: 10.1021/acs.langmuir.8b00996
16. Noh H, Liew SF, Saranathan V, Mochrie SGJ, Prum RO, Dufresne ER & Cao H (2010) How noniridescent colors are generated by quasi-ordered structures of bird feathers. *Advanced Materials* **22(26-27)** 2871-2880. https://doi: 10.1002/adma.200903699
17. Saegusa M, Kurokawa H, Takahashi N, Takamizawa T, Ishii R, Shiratsuchi K & Miyazaki M (2020) Evaluation of color matching ability of a structural colored resin composite *Operative Dentistry* August 19 Online ahead of print. https://doi: 10.2341/20-002-L.
18. Pereira Sanchez N, Powers JM, & Paravina RD (2019) Instrumental and visual evaluation of the color adjustment potential of resin composites *Journal of Esthetic and Restorative Dentistry* **31(5)** 465-470. https://doi: 10.1111/jerd.12488
19. Luo J, Qu D, Tikhonov A, Bohn J, & Asher SA (2010) Monodisperse, high refractive index, highly charged ZnS colloids self assemble into crystalline colloidal arrays *Journal of Colloid and Interface Science* **345(2)** 131-137. https://doi: 10.1016/j.jcis.2010.02.002
20. Price RB, Ferracane JL, & Shortall AC (2015) Light-curing units: a review of what we need to know *Journal of Dental Research* **94(9)** 1179-1186. https://doi: 10.1177/0022034515594786
21. International Organization for Standardization (2009) ISO 4049:2009. Dentistry Polymer-based restorative materials. *International Organization for Standardization*, Geneva, Switzerland. https://www.iso.org/standard/42898.html
22. Peutzfeldt A & Asmussen E (1992) Modulus of resilience as predictor for clinical wear of restorative resins *Dental Materials* **8(3)** 146-148. https://doi:10.1016/0109-5641(92)90071-j
23. Hata T, Kitazato Y, & Saito T (1987) Estimation of the surface energy of polymer solids *Journal of Adhesion* **21(3-4)** 177-194.
24. Sideridou ID, Karabela MM, & Vouvoud EC (2011) Physical properties of current dental nanohybrid and nanofill light-cured resin composites *Dental Materials* **27(6)** 598-607. https://doi: 10.1016/j.dental.2011.02.015
25. Ilie N, Rencz A, & Hickel R (2013) Investigations towards nano-hybrid resin-based composites *Clinical Oral Investigations* **17(1)** 185-193. https://doi: 10.1007/s00784-012-0689-1
26. Powers JM & Wataha JC (2013) Dental Materials: Properties and Manipulation, 10th ed., Mosby, Elsevier, Missouri, 15–21.
27. Shibasaki S, Takamizawa T, Nojiri K, Imai A, Tsujimoto A, Endo H, Suzuki S, Suda S, Barkmeier WW, Latta MA, & Miyazaki M (2017) Polymerization behavior and mechanical properties of high-viscosity bulk fill and low shrinkage resin composites *Operative Dentistry* **42(6)** E177-187. https://doi.org/ 10.2341/16-385-L
28. Barszczewska-Rybarek IM (2009) Structure-property relationships in dimethacrylate networks based on Bis-GMA, UDMA and TEGDMA *Dental Materials* **25(9)** 1082-1089. https://doi: 10.1016/j.dental.2009.01.106

29. Jung M (1997) Surface roughness and cutting efficacy of composite finishing instruments *Operative Dentistry* **22(3)** 98-104.

30. Roeder LB, Tate WH, & Powers JM (2000) Effect of finishing and polishing procedures on the surface roughness of packable composites *Operative Dentistry* **25(6)** 534-543.

31. Watanabe T, Miyazaki M, & Moore BK (2006) Influence of polishing instruments on the surface texture of resin composites *Quintessence International* **37(1)** 61-67.

32. Kaizer MR, Oliveria-Ogliari A, Cenci MS, Opdam NJM, & Moraes RR (2014) Do nanofill or submicron composites show improved smoothness and gloss? A systematic review of in vitro studies *Dental Materials* **30(4)** e41–e78. https://doi: 10.1016/j.dental.2014.01.001

33. Rodrigues-Junior SA, Chemin P, Piaia PP, & Ferracane JL (2015) Surface roughness and gloss of actual composites as polished with different polishing systems *Operative Dentistry* **40(4)** 418-429. https://doi: 10.2341/14-014L

34. Cazzaniga G, Ottobelli M, Ionescu AC, Paolone G, Gherlone E, Ferracane JL, & Brambilla E (2017) In vitro biofilm formation on resin-based composites after different finishing and polishing procedures *Journal of Dentistry* **67** 43–52. https://doi: 10.1016/j.jdent.2017.07.012

35. Heintze SD, Forjanic M, & Rousson V (2006) Surface roughness and gloss of dental materials as a function of force and polishing time *in vitro Dental Materials* **22(2)** 146-165. https://doi: 10.1016/j.dental.2005.04.013

36. Antonson SA, Yazici AR, Kilinc E, Antonson DE, & Hardigan PC (2011) Comparison of different finishing/polishing systems on surface roughness and gloss of resin composites *Journal of Dentistry* **39 (Supplement 1)** e9-e17. https://doi: 10.1016/j.jdent.2011.01.006

37. da Costa JB, Goncalves F, & Ferracane JL (2011) Comparison of two-step versus four-step composite finishing/polishing disc systems: Evaluation of a new two-step composite polishing disc system *Operative Dentistry* **36(2)** 205-212. https://doi: 10.2341/10-162-L

38. Cook MP & Thomas K (1990) Evaluation of gloss meters for measurement of moulded plastics. *Polymer Testing* **9(4)** 233-244. https://doi.org/10.1016/0142-9418(90)90010-B

39. Imai A, Takamizawa T, Sai K, Tsujimoto A, Nojiri K, Endo H, Barkmeier WW, Latta MA, & Miyazaki M (2017) Influence of application method on surface free-energy and bond strength of universal adhesive systems to enamel *European Journal of Oral Science* **125(5)** 385-395. https://doi: 10.1111/eos.12361

40. Saito S, Takamizawa T. Ishii R, Tsujimoto A, Hirokane E, Barkmeier WW, Latta MA, & Miyazaki M (2020) Influence of application time on dentin bond performance in different etching modes of universal adhesives *Operative Dentistry* **45(2)** 183-195. https://doi: 10.2341/19-028-L

41. Venz S & Dickens B (1991) NIR-spectroscopic investigation of water sorption characteristics of dental resins and composites *Journal of Biomedical Materials Research* **25(10)** 1231-1248. https://doi: 10.1002/jbm.820251005