

## Article

# Effect of Two-Step Polishing Systems on the Surface Roughness of Bulk Fill Resin Composites: An In-Vitro Study

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## Abstract

This study evaluated the effect of two-step polishing procedures on the surface roughness of bulk fill restorative materials. Disk-shaped specimens (10 × 1.5 mm) were prepared from four resin composites: Filtek One Bulk Fill (3M ESPE) and Tetric PowerFill (Ivoclar Vivadent), both bulk fill nanohybrid composites; X-tra fil LC (Voco), a bulk fill microfilled composite; and Filtek Supreme (3M ESPE), a conventional nanofilled composite used as a control. Polishing was performed using D-Fine Double Diamond, Sof-Lex Diamond, and A.S.A.P. polishers. Each system was applied for 30 s with a slow-speed handpiece at 10,000 rpm under water cooling. Surface roughness (Ra) was measured before and after polishing using a profilometer, with three readings per specimen, and surface morphology was assessed by scanning electron microscopy. Data were analyzed using two-way ANOVA and Tukey's HSD test ( $\alpha = 0.05$ ). Significant differences were observed for the interaction between composite type and polishing system ( $p < 0.001$ ). The lowest Ra value was obtained for Filtek One polished with Sof-Lex Diamond, while the highest surface roughness was observed for X-tra fil LC polished with D-Fine ( $0.800 \pm 0.072 \mu\text{m}$ ). SEM analysis indicated that composites containing larger filler particles exhibited greater surface roughness. In conclusion, surface roughness after polishing was primarily material dependent, with nanofilled composites demonstrating superior polishability compared to materials with larger filler particles.

**Keywords:** polishing; surface roughness; composite resin; bulk fill



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## 1. Introduction

Advances in composite materials and adhesive techniques have established resin composites as the most widely used direct restorative material in dentistry. Their favorable mechanical and physical properties allow for the replication of dental structures, facilitated by their command-set capability, and the ease of adjustment and repair. Additionally, their polishability enhances wear resistance, smoothness, and gloss, contributing to favorable clinical performance [1,2]. Bulk fill resin composites have gained widespread acceptance in restorative dentistry due to efficient light-curing at thickness of up to 4–5 mm, offering a faster and more predictable alternative to the traditional incremental layering technique.

Moreover, bulk fill resin composites reduce the risk of void formation between successive layers, a limitation commonly associated with incremental placement protocols, [3–5] and have been reported to generate lower polymerization stress and reduced post gel shrinkage [6]. These characteristics are attributed to the use of more reactive photoinitiator systems, increased translucency, chemically modified monomers, and optimized filler technology [3–5].

To enhance clinical longevity, restorative materials should achieve a surface smoothness comparable to that of natural enamel after polishing, as increased surface roughness (Ra) has been associated with greater susceptibility to plaque accumulation, which may lead to organic acid production, softening of the resin matrix, and increased susceptibility of the surface to staining [3,7–12]. The surface of resin composite materials is particularly susceptible to bacterial plaque accumulation, especially by *Streptococcus mutans*, a primary contributor to cariogenic biofilm formation and the onset of secondary caries [7]. Maximizing the surface quality of composite restorations has been shown to prolong their clinical lifespan by reducing biofilm development [3,8–10]. Furthermore, as the tip of the tongue can perceive differences in surface roughness ranging from approximately 0.25 to 0.5  $\mu\text{m}$ , attaining a smooth restorative surface enhances patient comfort and overall satisfaction [13]. An additional key objective of the polishing protocol is to improve esthetic outcomes by increasing surface gloss while removing rough areas that could contribute to accelerated surface wear [14]. Surface roughness (Ra) is thus a key factor in restoration success and is typically assessed quantitatively using profilometry and qualitatively through scanning electron microscopy (SEM) [15,16].

A variety of finishing and polishing techniques are available to enhance the surface properties of composite restorations. Finishing techniques aim to optimize the shape of the restoration by reducing excess material and refining the contours, whereas polishing techniques focus on minimizing the scratches introduced during the finishing process, resulting in a smoother surface [17]. Although polishing systems may differ in shape and mode of action, they generally involve the sequential use of abrasives with progressively finer grit sizes, most commonly based on aluminum oxide or diamond particles dispersed in silicone rubber [18–20]. The surface morphology of resin composites following finishing and polishing procedures is influenced by a range of intrinsic and extrinsic factors. Given the importance of achieving a smooth surface to minimize bacterial adhesion and enhance the clinical longevity of restorations, it is essential to understand how different polishing systems affect the surface roughness of contemporary resin composites, particularly in light of the limited data regarding the interaction between newly developed polishing systems and bulk fill resin composites. Therefore, this study aimed to investigate the effect of two-step polishing procedures on the surface roughness (Ra) of three bulk fill resin composites and one conventional resin composite used as a control. The tested null hypotheses were as follows: (i) the type of resin composite, and (ii) the type of polishers would exert no influence on the surface roughness of the tested materials.

## 2. Materials and Methods

### 2.1. Specimen Fabrication

A total of 128 specimens were prepared using a stainless-steel ring matrix with a central cavity measuring  $10 \times 1.5$  mm (diameter  $\times$  thickness). Four high-viscosity resin composites, bulk fill nanohybrid Filtek One Bulk Fill (3M ESPE, St. Paul, MN, USA), bulk fill nanohybrid Tetric PowerFill (Ivoclar Vivadent, Schaan, Liechtenstein), bulk fill microfilled X-tra fil LC (Voco, Cuxhaven, Germany), and a conventional nanofilled composite, Filtek Supreme (3M ESPE, St. Paul, MN, USA) (control), were used. A polyester (Mylar) strip and a 1 mm-thick clear glass slide were placed on the top and bottom of the metal mold, then

gently pressed to remove excess material and create a flat, smooth surface. Table 1 presents the composition of the resin composites used in this study.

**Table 1.** Composite resins used in the study and the composition as provided by their respective manufacturers.

| Resin Composite      | Matrix                                                                                                  | Filler Particles                                                                                    | Filler (by wt%) | Recommended Thickness | Manufacturer                               | Lot Number        |
|----------------------|---------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------|-----------------|-----------------------|--------------------------------------------|-------------------|
| Filtek Supreme       | Bis-GMA, UDMA, TEGDMA, and Bis-EMA                                                                      | silica filler, zirconia filler, and aggregated zirconia/silica cluster filler                       | 72.5%           | 1.5 mm                | 3M ESPE Dental Products, St. Paul, MN, USA | 10361128          |
| Filtek One Bulk Fill | AFM, AUDMA, UDMA and 1, 12-dodecane-DMA                                                                 | silica filler, zirconia filler, aggregated zirconia/silica cluster filler and ytterbium trifluoride | 76.5%           | 4 mm                  | 3M ESPE Dental Products, St. Paul, MN, USA | 10368775          |
| Tetric PowerFill     | Bis-GMA, Bis-EMA, UDMA, propoxylated bisphenol A dimethacrylate, DCP, $\beta$ -allyl sulfone AFCT agent | barium glass, ytterbium trifluoride, mixed oxide and copolymers                                     | 79–80%          | 4 mm                  | Ivoclar Vivadent, Schaan, Liechtenstein    | Z04XML and Z0S372 |
| X-Tra Fil LC         | Bis-GMA, UDMA, TEGDMA                                                                                   | Inorganic filler in methacrylate matrix                                                             | 86%             | 2 mm                  | VOCO, GmbH, Cuxhaven, Germany              | 2327724           |

Bis-GMA: bisphenol A-diglycidyl dimethacrylate; UDMA: urethane dimethacrylate; TEGDMA: triethylene glycol; Bis-EMA: ethoxylated bisphenol A dimethacrylate; AFM: addition-fragmentation monomer; AUDMA: aromatic dimethacrylate; DMA: dimethacrylate; DCP: tricyclodecane–dimethanol dimethacrylate; AFCT: addition fragmentation chain transfer.

Each increment was light-cured using a LED curing unit (VALO, Ultradent, South Jordan, UT, USA) in standard mode, delivering a radiant exitance of 1200 mW/cm<sup>2</sup> for 20 s. To complete polymerization, the specimens were stored in distilled water at 37 °C for 24 h. Surface roughness was initially measured on the Mylar-finished surface (control). These values were later compared to those obtained after polishing procedures. Table 2 provides details of the polishing systems evaluated in this study.

**Table 2.** Polishing systems used in this study.

| Polisher                                                                    | Composition                                                                                                                                                          | Manufacturer                                                  | Lot Number |
|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|------------|
| D-fine Double Diamond: Primary Polisher and Final High Shine Polisher       | Pre-polisher (purple): diamond particles with a size of 45 $\mu$ m<br>Final polisher (orange): size of 5 $\mu$ m<br>Pre-polisher (purple): aluminium oxide particles | Clinician's Choice Dental Products Inc., New Milford, CT, USA | 2307000017 |
| Sof-Lex: Pre-Polishing Spiral and Diamond Polishing Spiral                  | Final polisher (beige): diamond particles and thermoplastic elastomer                                                                                                | 3M ESPE Dental Products, St. Paul, MN, USA                    | 10062456   |
| A.S.A.P. *: Pre-Polisher Diamond Brushes and Final Polisher Diamond Brushes | Pre-polisher (purple): diamond particles with a size of 44 $\mu$ m<br>Final polisher (peach): size of 3–6 $\mu$ m                                                    | Clinician's Choice Dental Products Inc., New Milford, CT, USA | 2307000007 |

A.S.A.P. \*: All Surface Access Polishers (Clinician's Choice).

## 2.2. Polishing Procedure

After storage in distilled water, the specimens were randomly divided into four groups ( $n = 8$ ) according to the assigned surface treatment protocol: DF—D-Fine Double Diamond (Clinician's Choice); SL—Sof-Lex Pre-Polishing Spiral and Diamond Polishing Spiral (3M ESPE); and AS—A.S.A.P. Pre-Polisher and Final Polisher Diamond Brushes (Clinician's Choice). To simulate clinical finishing procedures and establish a standardized baseline surface roughness, the top surface of each specimen, except for those in Group 1 (MM—Mylar, control), was abraded with 600-grit silicon carbide sandpaper (3M ESPE) for 30 s, following established protocols for *in vitro* polishing [21]. Subsequently, the specimens were subjected to one of the following polishing protocols by a single calibrated operator at 10,000 rpm. To ensure standardization and control operator-dependent variables, a constant perpendicular application angle ( $90^\circ$ ) was maintained throughout all polishing procedures, and light tactile pressure (approximately 1–2 N) was applied using a modified handpiece with minimal hand support, following the protocol described by Heintze et al. for pressure-controlled polishing [22]. Each polisher was applied for 30 s under water cooling, in accordance with the manufacturer's instructions. After each polishing step, specimens were rinsed with water for 10 s and air-dried. A new polishing instrument was used for each specimen to avoid wear effects. The specimens were then grouped for comparative evaluation of surface roughness outcomes.

## 2.3. Finishing and Polishing Protocol

The specimens were allocated in four groups, according to the polishing system:

- Group 1: (MM)—Mylar strip (control): No finishing or polishing procedures were applied to this group.
- Group 2: (DF)—D-Fine Double Diamond Primary Polisher and D-Fine Double Diamond Final High Shine Polisher: Specimens were sequentially polished with a fine-grit spiral containing diamond particles (purple) and a superfine brush containing diamond particles (orange).
- Group 3: (SL)—Sof-Lex Pre-Polishing Spiral and Diamond Polishing Spiral: Specimens were sequentially polished with a fine-grit spiral containing aluminum oxide ( $\text{Al}_2\text{O}_3$ ) (purple) and a superfine spiral containing diamond particles (beige).
- Group 4: (AS)—A.S.A.P. Pre-Polisher and Final Polisher Diamond Brushes: Specimens were sequentially polished with a fine-grit spiral containing diamond particles (purple) and a superfine brush containing diamond particles (peach).

## 2.4. Surface Roughness Measurement

The arithmetic mean surface roughness ( $R_a$ ) was measured using a calibrated surface profilometer (SJ-201, Mitutoyo, Kanagawa, Japan) in accordance with ISO 4287:1997 [23] and ISO 4288:1996 [24]. Measurements were conducted in the horizontal direction of each specimen using a cut-off length ( $\lambda_c$ ) of 0.8 mm, a tracing length of 4 mm, and a stylus speed of 0.25 mm/s. Three parallel measurements were performed at distinct regions of each specimen (left, central, and right areas). The average of these three readings was calculated and recorded as the representative  $R_a$  value for each specimen. The profilometer was periodically recalibrated throughout the measurement process to ensure accuracy and consistency.

## 2.5. SEM Examination

One representative specimen from each group was selected for qualitative surface morphology assessment using SEM (Hitachi SU3500 variable pressure SEM). The selected specimens exhibited  $R_a$  values closest to the group mean, ensuring representativeness

of the surface characteristics. Since the specimens are nonconductive, they were initially sputter coated with a thin layer of gold (approximately 10 nm thickness) using a coating device (HUMMER VI Sputtering System) for 60 s to prevent charging artifacts. Following coating, the samples were placed on the SEM holder and SEM images were obtained from the most representative areas at a magnification of  $\times 1000$  (scale bar = 10  $\mu\text{m}$ ) and using an accelerating voltage of 5 kV. The SEM images were collected in secondary electron (SE) mode which produces a detailed, high-resolution image highlighting the sample's surface topography, including filler particle exposure, surface scratches, and matrix-filler interfaces.

## 2.6. Statistical Analysis

Statistical analyses were performed using Statistica for Windows (StatSoft, Tulsa, OK, USA). Surface roughness was the primary variable used for sample size calculation. A significance level of 0.05, a statistical power ( $1 - \beta$ ) of 0.80, and an effect size of 1.5 were adopted, resulting in a calculated sample size of  $n = 8$  per group. Prior to inferential testing, the normality of the data and the homogeneity of variances were assessed using the Shapiro–Wilk test. The results confirmed that the data were normally distributed and that the variances were homogeneous. Subsequently, a two-way analysis of variance (ANOVA) was conducted to evaluate the effects of resin composite type and polishing system on surface roughness. Post hoc comparisons were carried out using the Tukey test, with a significance level set at  $\alpha = 0.05$ .

The assumed effect size ( $f = 1.5$ ) was based on previously reported differences in surface roughness between composite materials subjected to distinct polishing protocols under controlled in vitro conditions. Given the known influence of filler particle size and polishing system characteristics on Ra values [7,8], this magnitude was selected to detect material-dependent variations exceeding the minimum threshold for clinical relevance, particularly with respect to surface roughness levels associated with increased biofilm accumulation.

## 3. Results

### 3.1. Quantitative Analyses of Surface Roughness (Ra)

The two-way ANOVA revealed that both the polishing system ( $F = 45.32$ ,  $p < 0.001$ , partial  $\eta^2 = 0.38$ ) and the type of resin composite ( $F = 52.17$ ,  $p < 0.001$ , partial  $\eta^2 = 0.42$ ) had a statistically significant effect on the final surface roughness with a significant interaction between factors ( $F = 8.95$ ,  $p < 0.001$ , partial  $\eta^2 = 0.25$ ). The results of the two-way ANOVA and post hoc Tukey test for surface roughness (Ra,  $\mu\text{m}$ ) are presented in Table 3.

**Table 3.** Means and Standard deviation of surface roughness Ra ( $\mu\text{m}$ ).

| Surface Roughness (Ra) | Mylar Strip (MS)                | D-Fine (DF)                      | Sof-Lex (SL)                    | A.S.A.P. (AS)                   |
|------------------------|---------------------------------|----------------------------------|---------------------------------|---------------------------------|
| Filtek™ Supreme        | 0.204 $\pm$ 0.057 <sup>Aa</sup> | 0.385 $\pm$ 0.052 <sup>Ab</sup>  | 0.395 $\pm$ 0.066 <sup>Ab</sup> | 0.433 $\pm$ 0.052 <sup>Ab</sup> |
| Filtek™ One            | 0.183 $\pm$ 0.037 <sup>Aa</sup> | 0.442 $\pm$ 0.072 <sup>Ab</sup>  | 0.370 $\pm$ 0.041 <sup>Ab</sup> | 0.484 $\pm$ 0.052 <sup>Ab</sup> |
| Tetric Powerfill       | 0.168 $\pm$ 0.046 <sup>Aa</sup> | 0.492 $\pm$ 0.101 <sup>Abc</sup> | 0.393 $\pm$ 0.051 <sup>Ab</sup> | 0.533 $\pm$ 0.104 <sup>Bc</sup> |
| X-tra Fil              | 0.177 $\pm$ 0.032 <sup>Aa</sup> | 0.800 $\pm$ 0.072 <sup>Bc</sup>  | 0.610 $\pm$ 0.140 <sup>Bb</sup> | 0.601 $\pm$ 0.118 <sup>Bb</sup> |

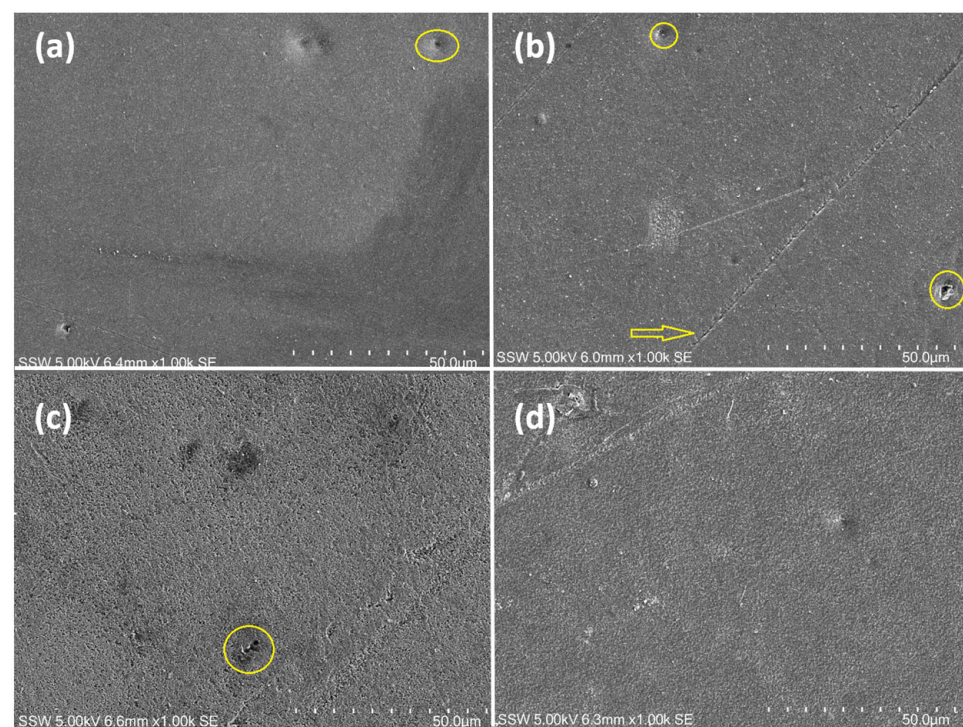
Uppercase letters indicate statistically similar surface roughness of composite materials (columns), while lowercase letters indicate statistically similar surface roughness of polishers (rows) ( $p < 0.05$ ).

No statistically significant differences in surface roughness were observed among the resin composites in the Mylar group (MM control), as confirmed by post hoc Tukey comparisons ( $p > 0.05$ ), which produced the smoothest surfaces across all materials. Tetric PowerFill and X-tra Fil exhibited significantly increased surface roughness after polishing with D-fine Double Diamond (DF) ( $0.492 \pm 0.101$  and  $0.800 \pm 0.072$ , respectively) and

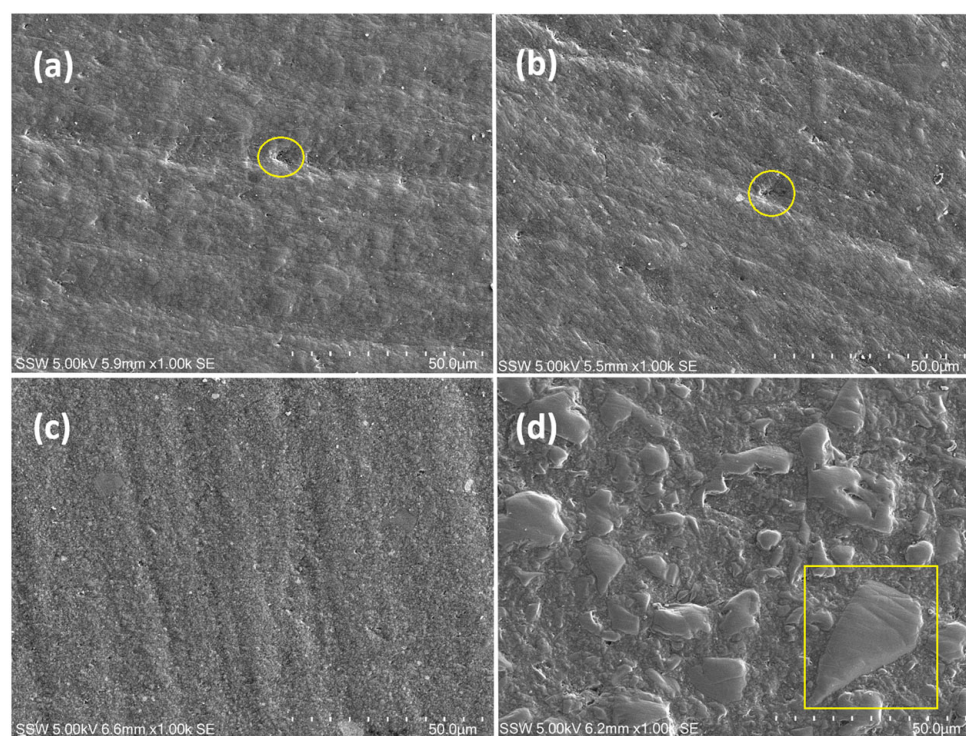
A.S.A.P. (AS) systems ( $0.533 \pm 0.104$  and  $0.601 \pm 0.118$ , respectively). For Tetric PowerFill, no statistically significant difference was found between the Sof-Lex (SL) and DF systems. In contrast, X-tra Fil displayed the highest surface roughness overall, with the DF group yielding the highest values for this material ( $0.800 \pm 0.072/p = 0.00158$ ). The conventional resin composite Filtek Supreme and its bulk fill counterpart, Filtek One, showed no statistically significant differences in surface roughness across the polishing protocols.

### 3.2. Scanning Electron Microscopy

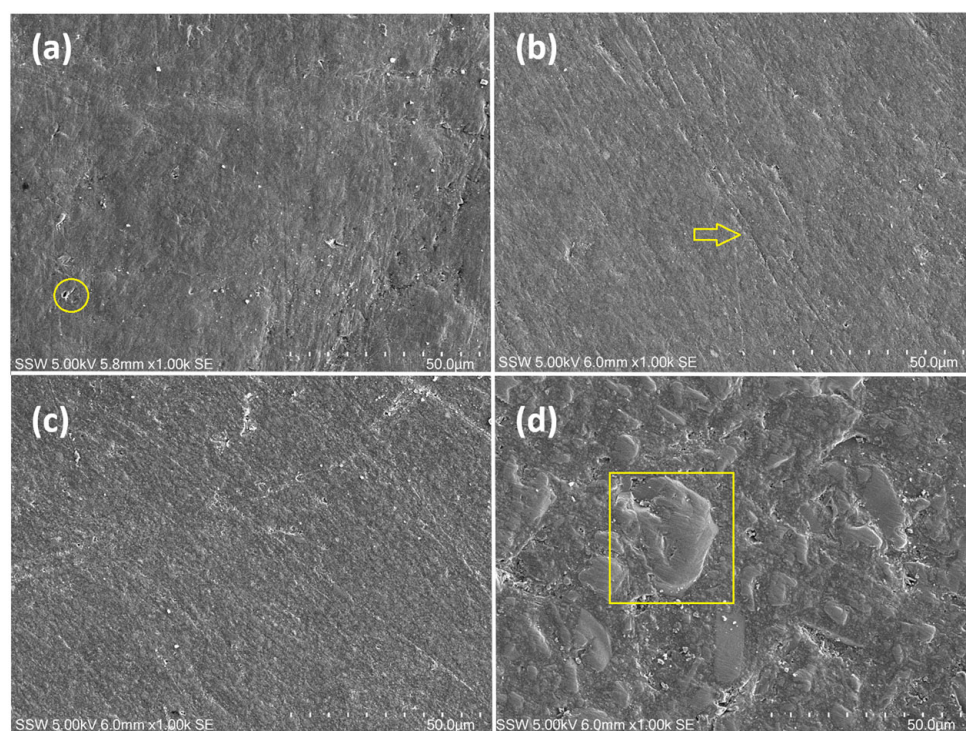
SEM analysis was performed at  $\times 1000$  magnification, with a scale bar corresponding to  $50\text{ }\mu\text{m}$ , to enable standardized qualitative comparison of surface morphology among groups. All specimens were prepared under identical sputtering conditions, and the images shown are representative of each experimental group. The SEM evaluation revealed the surface morphology of each composite resin following treatment with different polishing systems. The micrographs illustrated the distinct shapes and sizes of filler particles embedded within the organic matrix of the resin composites examined (Figures 1–4). Post-polishing evaluation showed noticeable exposure of filler particles in the X-tra Fil composite, likely resulting from the preferential abrasion of the organic matrix by the polishing instruments. These morphological findings provide a plausible explanation for the higher surface roughness observed in the X-tra Fil composite resin.



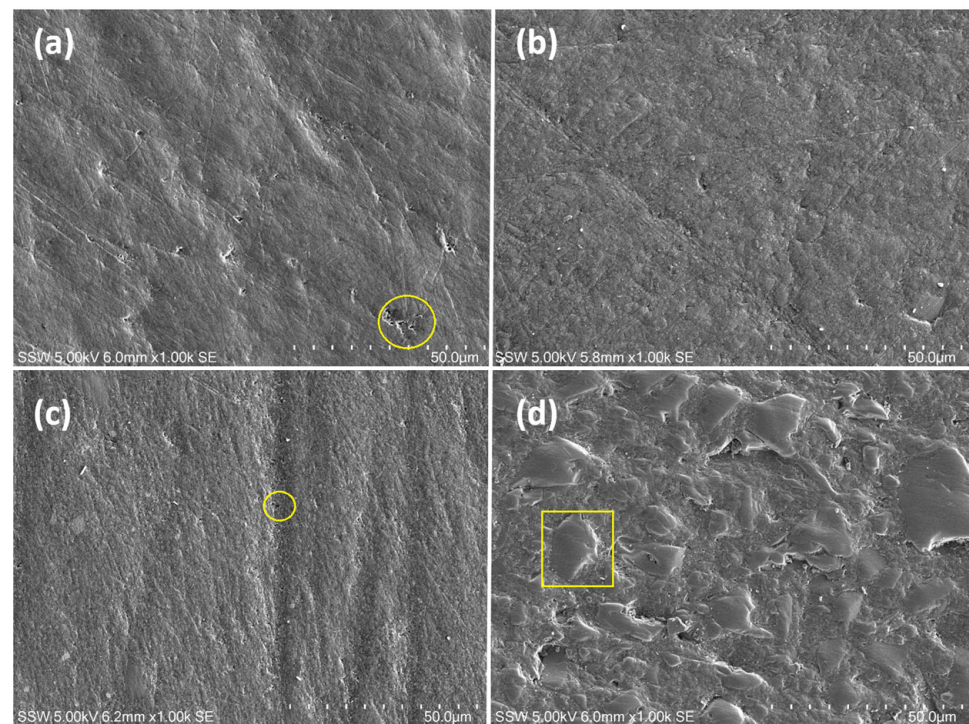
**Figure 1.** Representative SEM micrographs of Mylar strip control group associated with the different composite resins. Circles indicate microporosities and arrows denote surface scratches. (a) Filtek™ Supreme; (b) Filtek™ One; (c) Tetric Powerfill; (d) X-tra Fil.



**Figure 2.** Representative SEM micrographs of D-fine polishing system group associated with the different composite resins. Circles indicate microporosities and squares highlight exposed filler particles. (a) Filtek™ Supreme; (b) Filtek™ One; (c) Tetric Powerfill; (d) X-tra Fil.



**Figure 3.** Representative SEM micrographs of Sof-Lex polishing system group associated with the different composite resins. Circles indicate microporosities, arrows denote surface scratches, and squares highlight exposed filler particles. (a) Filtek™ Supreme; (b) Filtek™ One; (c) Tetric Powerfill; (d) X-tra Fil.



**Figure 4.** Representative SEM micrographs of A.S.A.P. polishing system group associated with the different composite resins. Circles indicate microporosities and squares highlight exposed filler particles. (a) Filtek™ Supreme; (b) Filtek™ One; (c) Tetric Powerfill; (d) X-tra Fil.

#### 4. Discussion

In the present study, two-step polishing systems were evaluated to investigate the effects of different polishing protocols on the surface roughness bulk fill resin composites. The findings revealed that both the polishing system and the type of resin composite had a statistically significant effect on the final surface roughness. Among the bulk fill resin composites tested, X-tra Fil exhibited a statistically significantly higher surface roughness (Ra) than the other composites, irrespective of the polishing system used, indicating a dominant material-dependent effect. In contrast, Tetric PowerFill exhibited increased surface roughness when polished with both the A.S.A.P. and D-Fine Double Diamond systems; however, its Ra values remained consistently lower than those observed for X-tra Fil, which showed the highest surface roughness overall. These results led to the rejection of the first null hypothesis, which stated no differences in surface roughness among the materials tested. Conversely, the conventional resin composite Filtek Supreme and its bulk fill counterpart, Filtek One, exhibited no statistically significant differences in surface roughness across the various polishing protocols, suggesting greater surface stability regardless of the polishing system used.

It is important to interpret these findings in light of clinically relevant surface roughness thresholds. Previous research has established that surface roughness values below approximately  $0.2\ \mu\text{m}$  are generally considered to minimize bacterial adhesion and biofilm accumulation, whereas values exceeding this threshold may increase the risk of plaque retention and secondary caries [7,8]. In the present study, the Mylar-finished control groups for all materials demonstrated Ra values below this critical threshold (ranging from  $0.168$  to  $0.204\ \mu\text{m}$ ), indicating inherently smooth surfaces. Following polishing procedures, Filtek Supreme and Filtek One maintained Ra values ranging from  $0.370$  to  $0.484\ \mu\text{m}$  across different polishing systems, which, although higher than the ideal threshold, remain within ranges generally considered clinically acceptable for composite restorations. In contrast, X-tra Fil consistently exceeded clinically acceptable roughness levels, reaching values as

high as 0.800  $\mu\text{m}$  with certain polishing systems, which may have significant implications for long-term clinical performance, particularly regarding plaque accumulation and stain susceptibility [25]. These findings underscore the importance of material selection and appropriate polishing protocols in achieving and maintaining surface quality conducive to favorable clinical outcomes.

The surface roughness of resin composites has been shown to be strongly affected by filler particle size, morphology, and distribution [8]. The low roughness values exhibited by Filtek Supreme and Filtek One resin composites is likely related to their nanotechnology-based filler systems, which incorporate non-agglomerated silica (~20 nm) and zirconia nanoparticles (~4–11 nm), along with zirconia/silica nanocluster fillers of similar size and morphology [26–28]. These fillers are homogeneously distributed within the resin matrix, minimizing the resin volume between particles and thereby limiting filler dislodgement and reducing surface irregularities [29]. Both Filtek Supreme and Filtek One incorporate nanocluster with overall filler sizes ranging from approximately 0.004 to 0.1  $\mu\text{m}$ , which support a high inorganic filler load [14,26,27]. Furthermore, nanometric resin composites, such as Filtek One and Tetric Powerfill, exhibit superior resistance to wear and abrasion, as their smaller particle size helps maintain the integrity of the resin matrix for a longer period [30].

Tetric PowerFill demonstrated comparable polishability across most polishing protocols; however, when polished with the A.S.A.P. system, it exhibited a significantly higher surface roughness. Tetric PowerFill incorporates a combination of barium aluminosilicate glass, isofillers (prepolymerized fillers composed of resin, glass, and ytterbium trifluoride), and mixed oxide fillers. Its filler system comprises a blend of nano-sized and larger glass particles, with the larger particles ranging approximately from 0.5 to 1.5  $\mu\text{m}$  [31]. This microstructural composition may explain the slightly increased surface porosity and roughness compared with composites formulated with exclusively nanofilled structures. Nonetheless, Tetric PowerFill still achieved relatively smooth surfaces following polishing. In contrast, X-tra Fil employs a multi-hybrid filler technology with a high filler loading (approximately 86 wt.%), presenting large inorganic particles that can exceed 20  $\mu\text{m}$  in size [32]. The inferior performance of X-tra Fil may be attributed with its larger filler particle size, which has been associated with increased susceptibility to microcracking and filler dislodgement during polishing procedures, resulting in greater surface irregularities [33,34]. A previous investigation also reported greater surface roughness for X-tra Fil compared with other nanohybrid bulk-fill resins when subjected to different polishing systems, corroborating the findings of this study [33,35].

With regard to the polishing systems evaluated, the results revealed material-dependent responses to the finishing procedures, thereby leading to the rejection of the second null hypothesis. Factors related to the polishing material, including abrasive type, composition, and particle size and shape influence the final surface smoothness. In this study, multi-step polishing systems were selected, as such protocols have consistently been shown to result in lower surface roughness values compared to single-step systems [32,36,37]. Tetric PowerFill bulk fill composite exhibited increased surface roughness when polished with both the A.S.A.P. and D-Fine Double Diamond systems. Similarly, X-tra Fil showed significantly higher roughness values, particularly following polishing with the D-Fine Double Diamond system, reaching an  $R_a$  value of 0.800  $\mu\text{m}$ , the highest among all tested materials in this study. These findings are consistent with previous research, which also reported elevated surface roughness values for X-tra Fil, especially when diamond-only abrasive systems were used [33].

The D-Fine Double Diamond Polishing System consists of a primary polisher embedded with diamond particles approximately 45  $\mu\text{m}$  in size, and a secondary polisher

containing a higher concentration of finer diamond particles of about 5  $\mu\text{m}$  [38]. The A.S.A.P. All Surface Access Polishers also present a dual-step approach. The pre-polisher incorporates diamond particles approximately 44  $\mu\text{m}$  in size, while the high-gloss polisher contains finer diamond particles ranging from 3 to 6  $\mu\text{m}$  [36]. On the other hand, The Sof-Lex Diamond Polishing System (Spiral Wheels) comprises a pre-polisher impregnated with aluminum oxide particles (~40–60  $\mu\text{m}$ ) and a final polisher composed of fine diamond particles (~3–6  $\mu\text{m}$ ) integrated into a thermoplastic elastomer matrix [39]. The Sof-Lex polishing system generally yielded smoother surfaces across the tested composites, with the exception of the microhybrid X-tra Fil, which exhibited significantly higher surface roughness. In agreement with the present findings, Kemaloğlu et al. found the Sof-Lex polishing system to be highly effective in reducing the surface roughness of nanohybrid resin composites [21].

The superior performance of the Sof-Lex Diamond Polishing System, despite containing abrasives of similar grit sizes to the other tested systems, warrants critical examination. While the D-Fine and A.S.A.P. systems utilize diamond particles exclusively (ranging from 3–6  $\mu\text{m}$  in the final step), the Sof-Lex system combines aluminum oxide in the pre-polishing step with diamond particles in the final polishing step, integrated into a flexible thermoplastic elastomer matrix. This combination may provide several advantages: (1) the initial use of aluminum oxide, which is slightly less aggressive than diamond, may reduce the creation of deep scratches that are difficult to remove in sub-sequent steps; (2) the thermoplastic elastomer matrix of the Sof-Lex final polisher may allow better adaptation to the composite surface and more uniform pressure distribution compared to the rubber-based matrices of the other systems; and (3) the spiral design of Sof-Lex polishers may provide more consistent contact with the surface compared to brush-type instruments. Additionally, the sequential use of different abrasive types (aluminum oxide followed by diamond) may be more effective than using diamond particles alone, as it progressively refines surface irregularities without introducing new deep scratches. These design features, rather than abrasive particle size alone, likely contribute to the enhanced polishing efficiency observed with the Sof-Lex system, particularly for nanofilled composites. However, for materials with large filler particles such as X-tra Fil, even the Sof-Lex system could not overcome the inherent challenges posed by the composite's microstructure, resulting in higher surface roughness values compared to nanofilled materials.

The combined use of profilometry and scanning electron microscopy (SEM) in the secondary electron mode, which emphasizes surface topography, provides a more comprehensive evaluation of the restorative surface and allows for better prediction of the restoration's clinical performance. Additionally, SEM is a valuable tool for identifying critical surface features, including exposed filler particles, polishing scratches, microdefects, matrix-filler debonding, and surface porosities, which assists in evaluating the response of restorative materials to polishing protocols. SEM observations directly corroborated the quantitative roughness measurements. For X-tra Fil, which exhibited the highest  $R_a$  values (up to 0.800  $\mu\text{m}$ ), SEM images revealed substantial exposure of large filler particles (exceeding 20  $\mu\text{m}$ ), prominent polishing scratches oriented in the direction of instrument application, and extensive areas of matrix removal exposing the underlying filler network. These morphological features explain the elevated roughness values, as the preferential removal of the organic matrix by abrasive instruments leaves protruding filler particles that contribute to increased surface irregularities. In contrast, the nanofilled composites (Filtek Supreme and Filtek One), which demonstrated lower  $R_a$  values (0.370–0.484  $\mu\text{m}$ ), exhibited relatively uniform surfaces with minimal filler exposure, fine polishing scratches, and better preservation of the matrix-filler interface. The homogeneous distribution of nanosized particles in these materials results in more uniform wear during polishing, with less pronounced

differences between matrix and filler hardness, thereby facilitating achievement of smoother surfaces. Tetric PowerFill showed intermediate features, with moderate filler exposure corresponding to its intermediate roughness values (0.393–0.533  $\mu\text{m}$ ). Smoother surfaces, as demonstrated by both profilometric and SEM analysis, are associated with reduced biofilm accumulation, enhanced wear resistance, improved color stability, and increased gloss, while also minimizing the risk of secondary caries and gingival inflammation [16,21,40].

The findings of the present study demonstrated that surface smoothness is significantly influenced by the interaction between the resin composite and the polishing system. Specifically, material-dependent factors including the type, shape, concentration, and size of inorganic filler particles within the resin matrix play a critical role in determining the final surface roughness, and may exert a greater influence on surface quality than the polishing system selected, as supported by previous studies [21,40–43]. These differences help explain the variation in surface performance across polishing protocols, particularly the superior outcomes observed with nanohybrid composites, which responded more favorably to modern polishing systems. Moreover, beyond the nature of the abrasive, other key factors, such as particle size, instrument design, and system flexibility, play a significant role in determining how efficiently the polisher interacts with the composite surface. Therefore, clinicians should take into account both the microstructural characteristics of the composite and the design features of the polishing system to achieve optimal surface smoothness and promote the long-term aesthetic and functional success of restorations.

The present study presents some limitations that should be considered when interpreting the results. As an *in vitro* investigation, it does not fully replicate the complexity of the oral environment, where factors such as tooth anatomy, cavity geometry, limited access and visibility, operator technique, the presence of saliva, and individual variability may significantly influence clinical outcomes. Additionally, the absence of artificial aging procedures such as thermocycling, mechanical loading, or toothbrushing simulation means that the findings represent only short-term polishing effectiveness and do not allow conclusions regarding the long-term durability of surface quality under clinical conditions. Aging processes, including exposure to oral fluids, pH cycling, thermal stress, and mechanical wear from mastication and hygiene procedures, could potentially alter surface roughness values over time and should be investigated in future studies. Furthermore, the study included a limited number of resin composites and polishing systems, which may affect the generalizability of the findings. The lack of precise control and quantification of polishing pressure, despite efforts to standardize operator technique, represents an additional limitation, as applied force may substantially affect final surface roughness, particularly for diamond-based polishing systems. Finally, the use of a single SEM specimen per group, while providing representative qualitative assessment of surface topography, limits the ability to draw generalized conclusions regarding morphological variations within each treatment group.

## 5. Conclusions

Within the limitations of this *in vitro* study, it can be concluded that the interaction between the resin composite structure and the polishing systems played a decisive role in determining the average surface roughness. The X-tra Fil bulk fill resin composite exhibited the highest surface roughness values across the different polishing systems when compared to the nanofilled materials. No statistically significant differences were observed between most bulk fill composites and the conventional resin composite (control), indicating that surface roughness was primarily material dependent.

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