

Original Article

Enhanced Bracket Retention on Reinforced Polyetheretherketone: Role of Specialized Primers in Shear Bond Strength

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ABSTRACT

This in vitro investigation evaluated how various primers influence the shear bond strength (SBS) and adhesive remnant index (ARI) of orthodontic brackets attached to a reinforced polyetheretherketone (PEEK) substrate. Forty samples were randomly divided into two groups based on the primer used during orthodontic bonding: Group 1 (control)—Transbond XT adhesive with Visio.link primer, and Group 2 (experimental)—Transbond XT adhesive with a conventional orthodontic primer. Following bonding, specimens underwent thermocycling, SBS testing, and ARI assessment after debonding. Statistical analysis was performed using the independent unpaired t-test and Chi-square test. Group 1 showed significantly higher SBS values (21.38 ± 1.48 MPa) than Group 2 (18.63 ± 1.29 MPa) ($p < 0.0001$). No statistically significant differences were noted in ARI scores or failure mode distribution between the groups. The SBS values from both primers exceeded the clinically acceptable threshold. Thus, both primers demonstrated comparable clinical applicability in orthodontic bonding, particularly in cases where Visio.link may not be readily accessible.

Keywords: Shear bond strength, PEEK, Orthodontic bonding, Adhesive primer, Metallic brackets, Bio-HPP

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Introduction

Achieving reliable bonding of orthodontic brackets is crucial for the overall success of orthodontic treatment [1]. In recent years, orthodontic treatment among adults has become increasingly popular [1–3]. Consequently, situations may arise where brackets must be bonded to restorative or prosthetic materials. Typically, when a fixed dental prosthesis is anticipated for an orthodontic patient, final prosthesis placement is deferred until orthodontic treatment concludes [1]. This postponement allows teeth to reach their final positions before restoration placement [2, 3]. Moreover, damage to the restoration during bracket removal could necessitate replacement [3]. To avoid such complications, temporary restorations are placed between orthodontic completion and final prosthesis

delivery, protecting the pulp, periodontal tissues, and preventing tooth decay or fractures [2, 4].

Computer-aided design/computer-aided manufacturing (CAD/CAM) systems now enable fabrication of pre-polymerized interim restorations that are more fracture-resistant and dimensionally accurate than directly fabricated ones [3]. Polymethyl methacrylate (PMMA) has long been used in CAD/CAM provisional restorations [5]. However, polyetheretherketone (PEEK), a high-performance polymer (HPP), has recently gained attention for long-term provisional and indirect restorations. PEEK is a thermoplastic, semi-crystalline aromatic polymer composed of repeating ether and ketone linkages along an aryl backbone [6, 7]. Its rising dental use is attributed to its bone-like elasticity modulus, high temperature and wear resistance, and outstanding chemical stability [8, 9]. Nonetheless, unmodified

PEEK's hydrophobic surface hinders adhesion with resin-based materials [10].

Reinforced or bioactive PEEK, commercially known as Bio-HPP, contains approximately 20% ceramic fillers [7, 8]. Its white shade, polishability, and strength make it a viable alternative for fixed prostheses [8]. Bio-HPP is particularly suitable for patients with bruxism, as it minimizes antagonist wear [7], and can be used in endo-crowns for restoring endodontically treated teeth in both adolescents and adults [7].

Bonding to reinforced PEEK remains a focus of ongoing research [11]. Mechanical surface treatments, such as airborne particle abrasion with aluminum oxide (Al_2O_3), with or without silica coating, have been proposed to enhance micromechanical retention and surface wettability [11, 12]. Chemical conditioning through adhesive primers—such as Visio.link® (Bredent, Germany) or Signum PEEK Bond® (Kulzer GmbH, Germany)—has also shown promise [12]. A combination of surface roughening and primer application enhances adhesion by increasing surface energy, introducing functional groups, and improving micro-retention [12].

Previous research has recommended combining mechanical pretreatment with the Visio.link primer to improve PEEK's shear bond strength (SBS) [12]. While Visio.link is widely advocated as the primer of choice for PEEK bonding [6, 12], a systematic review by Gama *et al.* [12] revealed that few studies have compared the SBS of PEEK bonded with various adhesives, limiting meta-analysis feasibility. Conversely, Lee *et al.* [13] found that a self-etching universal primer containing both MDP and silane coupling agents could serve as a viable alternative to Visio.link. Given that Visio.link may not always be accessible in orthodontic settings, the use of orthodontic primers on PEEK warrants investigation. Therefore, this study aimed to compare the effects of two primers—the manufacturer's recommended Visio.link and a conventional orthodontic primer—on the shear bond strength (SBS) and adhesive remnant index (ARI) of metallic brackets bonded to reinforced PEEK. The null hypothesis was that no significant difference in SBS would be observed between brackets bonded with either primer.

Materials and Methods

Specimen preparation

Based on sample size estimations from earlier publications [14], forty specimens were selected (20 per condition) to detect relevant differences in shear bond strength (SBS). Pre-fabricated PEEK discs (breCAM, Bio-HPP; Bredent GmbH, Senden,

Germany) were sectioned into blocks measuring $5 \times 7 \times 2 \text{ mm}^3$. The cuts were performed using an automated diamond saw (Isomet® 4000, Buehler, Lake Bluff, IL, USA) rotating at 2500 rpm under water irrigation to avoid overheating [15].

Each piece was then mounted vertically in self-cured acrylic resin (Acrostone Dental and Medical Supplies, Cairo, Egypt) within cylindrical molds (**Figure 1a**). The exposed surfaces were ground flat and smoothed sequentially using P600 and P800 grit silicon carbide abrasives (3M™, St. Paul, MN, USA) at 300 rpm with continuous water flow on an automatic polisher (LaboPol-25, Struers GmbH, Copenhagen, Denmark). All finishing was carried out by the same operator (H.R.M.) to maintain uniformity. After preparation, specimens were placed in an ultrasonic cleaner (Krisbow CD4862, Shenzhen, China) with distilled water for 10 minutes, then air-dried before surface modification [5, 16–18].

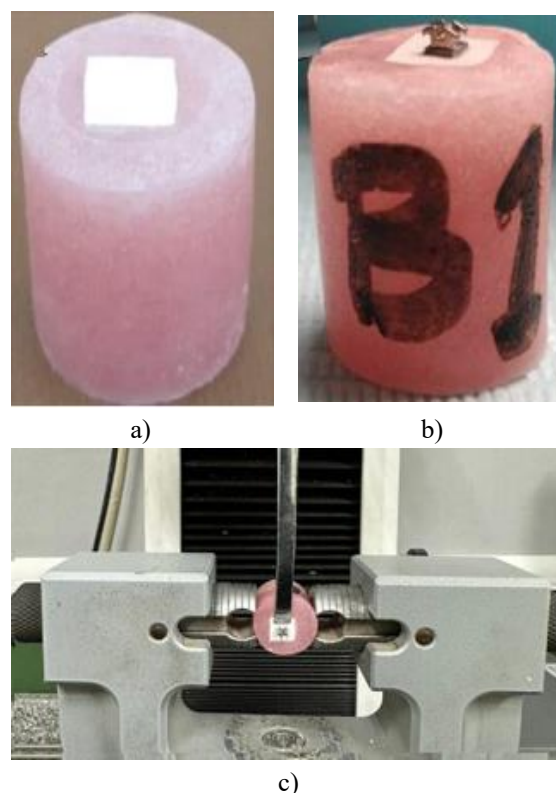


Figure 1. Stages of sample preparation and SBS testing: (a) embedding of PEEK blocks; (b) bracket bonding; (c) test alignment in the universal testing system.

Surface treatment and grouping

All specimens were air-abraded using $110 \mu\text{m } Al_2O_3$ for 30 seconds at 0.25 MPa, maintaining a 10 mm nozzle distance. The samples were again cleaned ultrasonically in distilled water for 10 minutes and air-dried for half a minute [5, 17–19]. The abraded

specimens were then divided randomly into two equal groups (n = 20) based on the primer used:

- Group 1 (Control): Visio.link primer (Lot: 210802; Exp: 02/24; Bredent GmbH & Co. KG, Senden, Germany).
- Group 2 (Test): Transbond XT primer (Lot: MB4GA; Exp: 05/24; 3M Unitek, Monrovia, CA, USA).

Bracket bonding

For Group 1, Visio.link was sprayed evenly from 15 mm distance, gently thinned with air, and polymerized for 90 seconds using a curing lamp delivering 1000 mW/cm² (Woodpecker, Guilin, Guangxi, China) [17]. Stainless steel lower incisor brackets (0.022-inch slot, Gemini series; 3M Unitek, Monrovia, CA, USA) with a 10.5 mm² base area were bonded using Transbond XT adhesive (Lot: MB4GA; Exp: 05/24). Excess composite was removed before light-curing for 40 seconds (**Figure 1b**) [20, 21].

In Group 2, the same distance and adhesive were used, but the Transbond XT primer was applied and polymerized for 10 seconds prior to bracket placement. All bonded samples were immersed in distilled water at 37 °C for 24 hours and subsequently subjected to 1500 thermal cycles between 5 °C and 55 °C, with 20-second dwell and 10-second transfer times to simulate intraoral temperature variation [22–24].

Shear bond strength (SBS) testing

Each specimen was randomly numbered to prevent evaluator bias. SBS testing was carried out using a universal testing machine (Instron Model 2710-113; Norwood, MA, USA). A chisel-edge rod applied a vertical load parallel to the bonding interface at a 1 ± 0.1 mm/min crosshead speed until debonding occurred (**Figure 1c**) [25–27].

The peak load at failure (in newtons) was divided by the bracket base area (10.5 mm²) to determine SBS, expressed in megapascals (MPa) [28].

Adhesive remnant index (ARI)

Post-testing, all samples were examined with a stereomicroscope (×20 magnification; Nikon SMZ745T, Tokyo, Japan). The residual adhesive on PEEK surfaces was categorized following the Adhesive Remnant Index (ARI) [29]:

- Score 0: No adhesive residue.
- Score 1: Adhesive covering ≤ 50% of surface.
- Score 2: Adhesive covering ≥ 50% of surface.
- Score 3: Complete adhesive coverage.

Scanning electron microscopy (SEM) evaluation

Representative samples from each condition were imaged under SEM (TESCAN VEGA, Brno-Kohoutovice, Czech Republic) to assess surface morphology after sandblasting and to observe residual adhesive after debonding.

Statistical evaluation

All data were processed using SPSS v24 (IBM Corp., Armonk, NY, USA). Descriptive statistics (means ± SD) were computed for both groups. Data normality was confirmed by Shapiro–Wilk and Kolmogorov–Smirnov tests. Since results followed a normal distribution, an independent t-test was applied to compare SBS values. Chi-square tests assessed ARI score distribution, and statistical significance was established at p ≤ 0.05.

Results and Discussion

Shear bond strength

The descriptive outcomes for both experimental groups are detailed in **Table 1**. For Group 1 (Visio.link primer), SBS readings varied from 18.70 MPa to 23.50 MPa, whereas Group 2 (Transbond XT primer) exhibited values between 16.75 MPa and 21.10 MPa. The 95% confidence intervals for the population means were calculated at 20.68–22.07 MPa for Group 1 and 18.03–19.24 MPa for Group 2. Collectively, these data reveal that specimens bonded with Visio.link demonstrated a higher mean SBS and slightly broader dispersion compared to those treated with Transbond XT primer.

Table 1. Descriptive summary of shear bond strength (SBS) values for both groups.

Descriptive Statistic	Group 1 (Transbond XT + Visio.link) N = 20	Group 2 (Transbond XT + Traditional Primer) N = 20
Minimum	18.70 MPa	16.75 MPa
25th Percentile	19.84 MPa	17.54 MPa
Median	21.84 MPa	18.52 MPa
75th Percentile	22.36 MPa	19.30 MPa
Maximum	23.50 MPa	21.10 MPa

Mean	21.38 MPa	18.63 MPa
Standard Deviation	1.48 MPa	1.29 MPa
Standard Error of Mean	0.33 MPa	0.28 MPa
95% CI Lower Bound	20.68 MPa	18.03 MPa
95% CI Upper Bound	22.07 MPa	19.24 MPa

As shown in **Figure 1**, the average SBS \pm SD for PEEK samples in Group 1 was 21.38 ± 1.48 MPa, while Group 2 recorded 18.63 ± 1.29 MPa. Results of the independent-samples t-test are presented in **Table 2**. The observed difference in mean SBS

between the two groups reached statistical significance ($p < 0.0001$). The two-tailed p-value verified that the hypothesis test was nondirectional, and a t-statistic of 6.237 ($df = 38$) confirmed the strength of this difference.

Table 2. Statistical comparison of mean SBS between groups (independent t-test).

Statistical Test	Result
Unpaired Independent t-Test	
p-value	<0.0001
Significant difference ($p < 0.05$)	Yes
Tailedness	Two-tailed
t-statistic, degrees of freedom	$t = 6.237, df = 38$

Adhesive remnant index (ARI)

The distribution of ARI scores and Chi-square results are listed in **Table 3**.

Within Group 1, no samples scored 0; 3 specimens (15%) scored 1, 11 (55%) scored 2, and 6 (30%) scored 3.

For Group 2, no samples scored 0; 5 specimens (25%) scored 1, 10 (50%) scored 2, and 5 (25%) scored 3. Statistical analysis using the Chi-square test demonstrated that these distributions did not differ significantly, indicating that bond failure behavior and adhesive residue were similar between Visio.link and Transbond XT primers.

Table 3. Chi-square comparison of ARI distributions between groups.

Group	ARI 0	ARI 1	ARI 2	ARI 3	Total	p-Value
Group 1	0	(3) 15%	(11) 55%	(6) 30%	20	0.6385 (NS)
Group 2	0	(5) 25%	(10) 50%	(5) 25%	20	—
p-value	—	0.4350 (NS)	0.7546 (NS)	0.7266 (NS)	—	—

Refer to section text for ARI scale; NS = non-significant difference.

Scanning electron microscopy (SEM) findings

Representative SEM micrographs of treated and debonded PEEK specimens are shown in **Figure 2**. The treated PEEK surface (**Figure 3a**) exhibited a rough, irregular morphology featuring distinct grooves and depressions. After debonding (**Figure 3b**), most regions displayed residual adhesive covering the bracket base area, corresponding to an ARI value greater than 2.

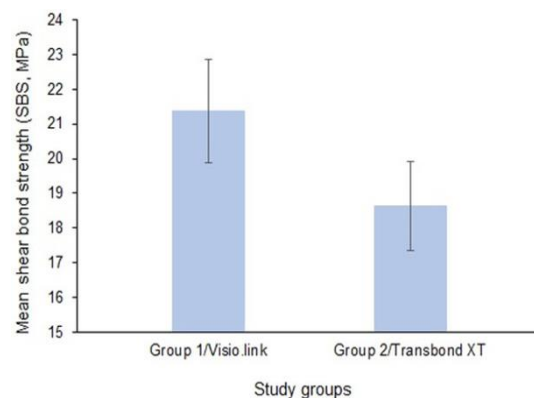


Figure 2. Shear bond strength comparison of the tested groups.

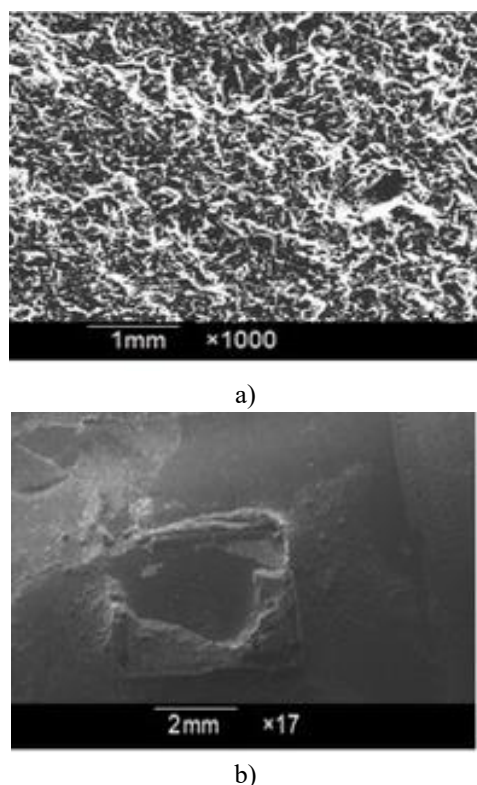


Figure 3. (a) Surface of PEEK following treatment; (b) PEEK surface post-debonding showing considerable adhesive remnants.

This research evaluated the bond strength of orthodontic brackets adhered to reinforced PEEK using either the manufacturer's recommended Visio.link primer or a traditional orthodontic primer. Based on the available literature, this appears to be the first investigation focusing on SBS between metallic orthodontic brackets and Bio-HPP type PEEK substrates.

The null assumption—that there would be no significant difference between primer systems—was disproven, as statistical testing confirmed a marked variation in bond strength results.

Previous studies have proposed that clinically sufficient SBS should lie between 6 and 8 MPa, whereas the maximum safe limit should remain below the enamel fracture level (≈ 14 MPa) [23, 30]. However, in vitro outcomes often exceed in vivo readings by approximately 40%, largely due to environmental complexities such as moisture and temperature fluctuations [31].

In the current study, mean SBS values reached 21.38 ± 1.486 MPa for Visio.link and 18.63 ± 1.291 MPa for Transbond XT. Although statistically significant, this numerical gap is unlikely to hold clinical importance since both primers achieved bond strengths well above the recommended threshold. Clinically, achieving adequate adhesion is preferable to overly strong

bonding, as excessive bond strength can complicate bracket removal [32].

For optimal outcomes, brackets bonded to prosthetic surfaces must endure functional and masticatory stresses throughout orthodontic treatment while allowing for safe debonding at completion, preventing any damage to restorative materials [33].

In this research, PEEK samples underwent surface conditioning through sandblasting. This approach was chosen because it represents a straightforward and safe intraoral pretreatment technique that enhances the surface roughness and contact area of PEEK, thus improving micromechanical adhesion. Furthermore, it effectively eliminates organic residues from the surface and facilitates surface activation [16, 33]. The Visio.link primer remains the standard adhesive primer recommended for PEEK, as it provides consistent resin bonding performance independent of surface pretreatment [16, 17]. However, due to limited accessibility, clinicians may need to substitute it with a conventional orthodontic primer. Despite the difference in primer types, Transbond XT adhesive was consistently used for bracket attachment in both experimental groups since it is considered the benchmark light-cured orthodontic bonding agent [21]. While most prior SBS investigations have employed premolar brackets, this study opted for mandibular incisor metal brackets, as their flat bases ensured optimal adaptation to the smooth PEEK surfaces [34]. Temperature variations in the oral cavity (ranging from 0 to 65 °C) can influence the adhesive interface of dental restorations. The International Organization for Standardization (ISO) prescribes a minimum of 500 cycles between 5 and 55 °C, with a 20-second dwell period and a transfer time of 5–10 seconds, to replicate intraoral temperature changes [35]. However, these 500 cycles approximate less than two months of clinical use and fail to represent the typical orthodontic treatment duration exceeding one year. Therefore, this investigation incorporated 1500 thermocycles between 5 and 55 °C to more closely reflect realistic intraoral thermal fatigue.

The shear bond strength (SBS) test is a commonly used procedure to evaluate adhesive performance in dental materials. Standard shear testing is favored due to its simplicity, minimal equipment requirements, and comprehensive insight into adhesive durability—although it remains controversial because of several uncontrolled influencing factors [35].

The Adhesive Remnant Index (ARI) serves as the most widely used and straightforward tool for assessing bond integrity between the substrate and the bracket base. This qualitative and subjective measure evaluates

the amount of adhesive left on the surface following debonding and indicates the site of bond failure [31, 32, 36]. It offers a fast and uncomplicated procedure that requires no specialized instruments. Earlier investigations revealed no meaningful variation in ARI results when comparing visual scoring, elemental mapping, and SEM evaluations [37, 38]. Conversely, the consistency of ARI results under varying magnification levels has been questioned [39].

A stronger interface between adhesive resin and substrate may result in surface microfractures, reflected by higher ARI values. Therefore, failures within the adhesive or between the bracket base and adhesive layer are preferable to reduce the risk of surface cracking or restoration damage during debonding [31, 40–42]. The present research observed no significant variation in failure modes. Most failures occurred at the bracket–adhesive junction in both groups, leaving most of the adhesive on the PEEK surface (scores 2 and 3) (**Figure 2b**). Past literature indicates that higher bond strength often corresponds to mixed-type fractures. Failures located at the bracket–adhesive interface, as denoted by scores 2 and 3, are ideal for safer debonding since most adhesive remains on the surface [43]. Nevertheless, surfaces should be polished thoroughly after bracket removal to eliminate residual adhesive.

This study had certain limitations. Despite attempts to replicate intraoral conditions, factors such as salivary effects, mastication forces, diet, and hygiene habits were not incorporated. Additionally, although significant differences in SBS values were noted between primer groups, these were not consistent with ARI outcomes. Moreover, the absence of prior data on orthodontic bonding to PEEK precluded direct comparison with existing research. Future studies should explore SBS behavior with PEEK crowns, aesthetic brackets, and alternative surface conditioning techniques. Further, evaluating immediate SBS rather than the 24-hour measurement would better reflect clinical conditions where archwires are attached shortly after bonding.

Conclusion

Within the limitations of this *in vitro* study, the following outcomes were obtained:

- Both primer types produced SBS values above the clinically acceptable threshold (6–8 MPa)
- The Visio.link primer achieved significantly higher SBS (21.38 ± 1.48) compared with the traditional Transbond XT primer (18.63 ± 1.29) ($p < 0.0001$).

- No significant variation was observed in failure types or ARI score distribution between the two primer groups.
- Both primers demonstrated comparable clinical viability for orthodontic bonding of metal brackets to PEEK.
- When Visio.link is unavailable, the conventional orthodontic primer can serve as a practical alternative for bonding to PEEK surfaces.

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