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Ceramic Inlay Bonded Interfaces in Minimally Invasive Preparations: Damage and Contributing Mechanisms in Sliding Contact

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Clinical Relevance

It is recommended for clinicians to avoid placing centric occlusion on the bonded interface and to adjust a distributed occlusion contact to reduce the contact stress for inlay cavities with an unconventional tooth marginal angle or an axial wall located at the cusp inclination.

SUMMARY

Background: In the preparation of inlay cavities, a choice must be made between conventional standard and minimally invasive preparation designs; in the long run, this choice can affect the integrity of the bonded interface.

Purpose: To evaluate the effect of minimally invasive cavity preparation designs on the extent and contributing mechanisms of damage to ceramic inlay bonded interfaces.

Methods and Materials: Tooth blocks with 90°, 120° and 75° marginal angles were prepared, representing tooth cavities with conventional

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standard and minimally invasive preparations with large divergence and convergence angles and bonded to monolithic ceramic (IPS e.max CAD). Vickers indentations were placed at various distances from the bonded interface. The indentation morphology and crack length were observed. Reciprocating wear tests were performed on the bonded interface with a 20-newton (N) vertical load. The wear depth and wear-scar morphology were characterized after increments of cyclic sliding contact.

Results: The 120° group exhibited longer indentation cracks in the ceramic, whereas the 75° group showed larger indentations in the enamel when compared to the 90° group (p<0.001). Consistent with the weaker edge crack resistance, the 120° group experienced the greatest wear (p=0.008), and the wear depth in the enamel of the 75° group exceeded that of the 90° group (p<0.001) in the early stage (5×102 cycles). However, no significant difference in the wear depth (p>0.147) and morphology were found at the later wear stage among the three groups.

Conclusion: Within the limitations of this study, minimally invasive preparations with 120° and 75° marginal angles can result in early sever damage at the ceramic inlay bonded interface but show comparable wear behaviors to the conventional 90° group at the later stage.

INTRODUCTION

Inlays are indirect restorations that are embedded within a tooth cavity to restore natural tooth morphology and function and are increasingly recommended by clinicians for minimally invasive treatment of tooth defects.[1] Among tooth-colored restorative materials, all-ceramic prostheses are preferred by doctors and patients due to better aesthetics, wear resistance, and chemical stability.[2]

The preparation of an inlay cavity is a necessary compromise to restore a damaged tooth. At the present time, various preparation guidelines exist for ceramic inlay restorations. According to the traditional preparation guideline, a divergence angle of approximately 6° to 10° between two internal axial walls is recommended in order to provide adequate retention force for restorations.[3-5] Nevertheless, with advancements in cement technology, the bond strength of present cement systems can exceed 50 megapascals (MPa),[6] no longer requiring a strict retention form for inlay restorations.[7,8] Alternatively, tooth preparation has come to be focused on maximal preservation of natural dental hard tissue, and a minimally invasive design should be considered for the given situation.[9-11]

After removal of the original filling or decayed tissue, the inlay tooth cavity might have a conventional divergence angle (Figure 1A2), an excessive divergence angle (Figure 1B2) or even a convergence angle (Figure 1C2). Accordingly, the marginal angle of the residual tooth structure could range from obtuse to acute. For cavities with a conventional divergence angle, the marginal angle of tooth tissue is also related to the location of the axial wall. When the axial wall is located at the central area of the occlusal surface, the marginal angle of the tooth tissue is about 90° (Figure 1A3). When the axial wall is located at the cusp inclination, however, the marginal angle is about 120° (Figure 1A3), due to the anatomic form of the tooth cusp.[3,4] In order to achieve a conventional divergent geometrical design in cavities with an excessive divergence angle or a convergence angle, following the traditional preparation guidelines would inevitably result in the removal of sound tooth tissue, especially the enamel near the occlusal surface of the cavity (Figure 1B3 and 1C3).[12,13] The removal of sound tooth tissue can be avoided in these situations by using a minimally invasive preparation. A cavity with a large divergence angle could be restored with an inlay restoration after a simple polishing treatment (Figure 1B4). However, the cement edge of the inlay restoration might be an acute angle, as this angle is determined by the beveled edge of the prepared tooth (Figure 2B2). For a tooth cavity with a convergence angle, a chamfer is not conducive to the production of models and prostheses. In this scenario, the proximal undercuts would be filled with resin composite or resin cement (Figure 1C4), resulting in a divergent geometrical form.[10,14] While the minimally invasive design might save more healthy tissue, it would also lead to a broader luting margin cervically (Figure 2C3).

The marginal angle of an inlay tooth cavity in the minimally invasive preparation design can be considered as falling into three categories in various situations: close to 90°, greater than 90°, or less than 90°. Considering the anatomic form of the tooth cusp and the parameter setting in previous studies,[4,10] marginal angles of 90°, 120° and 75° were selected for this study.

A requirement for long-term stability of an inlay restoration is an intact bonded interface.[15, 16] Destruction of interface integrity under chewing force is closely related to the occurrence of complications such as dentin sensitivity, marginal discoloration,

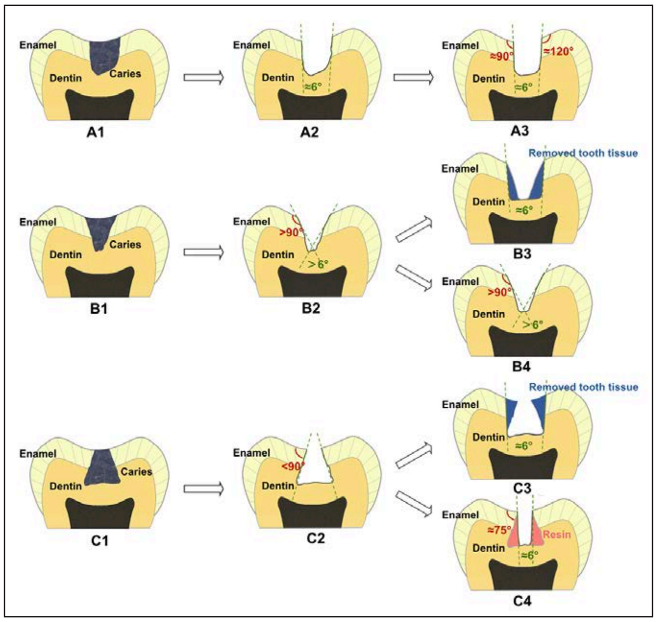

Figure 1. *Description of the experimental groups. (A1-C1): different types of decayed teeth; A2-C2: cavities remaining after removal of the original filling or decayed dental tissue; (B3, C3): inlay cavities in conventional standard preparation. (A3, B4, C4): inlay cavities in minimally invasive preparations.*

secondary caries, and prosthesis fracture.[17-20] A previous study indicated that minimally invasive preparations for mesial-occlusal-distal (MOD) inlays with undercuts show marginal adaptation equivalent to that of conventional preparation designs,[10] thereby serving as a preliminarily justification for their clinical application. Apart from internal adaptation, differences in marginal angle of the tooth tissue and ceramic inlay may influence the interface degradation process of inlay-restored teeth, because they lead to different stress distributions and marginal toughness at the bonded interface between tooth and restoration.[21-25] However, whether minimally invasive preparations will affect the stability of the bonded interface has not been reported.

The purpose of this study was to evaluate the effect of minimally invasive cavity preparation designs on the extent and contributing mechanisms of damage to bonded interfaces involving ceramic inlays by using reciprocating sliding wear tests. Due to the brittle nature of the materials, cracks may appear in the ceramic or enamel surface when stress intensity exceeds fracture toughness.[26,27] These cracks can undergo cyclic extension under the repetition of contact stress, and their intersection with each other can result in peeling and degradation of the bonded interface. Therefore, we introduced an indentation near the bonded interface to analyze crack behavior before analyzing damage under cyclic sliding contact. The null hypothesis was that the minimally invasive preparations would not affect the characteristics of the damage in bonded interfaces involving ceramic inlays.

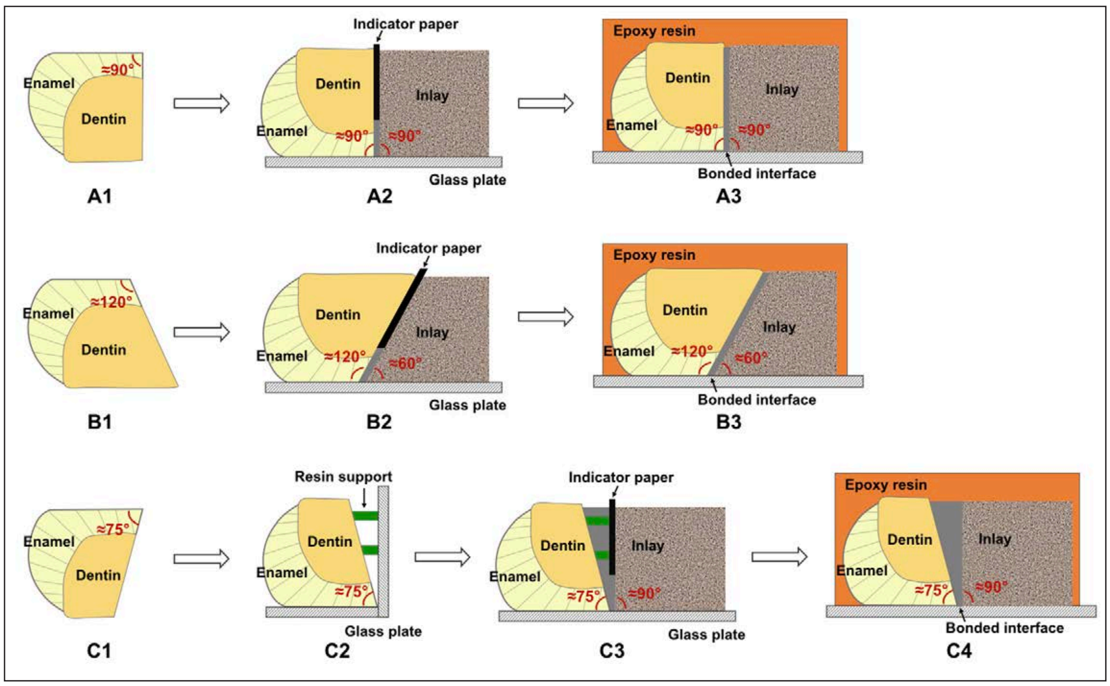

Figure 2. *Description of the specimen bonding procedures (section view). (A1-C1): tooth sections with flat occlusal surfaces; C2: tooth sections of 75° group with two resin supports; (A2, B2, C3): schematic diagram of the bonded specimens; (A3, B3, C4): the embedded specimens.*

METHODS AND MATERIALS

Specimen Preparation

The crowns of freshly extracted third molars (patient age: 18 years to 25 years) were cut into two sections along the mesial-distal axis with a slow diamond-abrasive slicing wheel (Struers Minitom, Struers) under continuous water coolant. The occlusal surfaces of tooth sections were ground flat with 280 grit silicon carbide (SiC) papers. A total of 90 tooth sections were assigned to three groups: the inner faces were ground to produce marginal angles of 90° (Figure 2A1), 120° (Figure 2B1), or 75° (Figure 2C1) and inspected with an angle ruler. Meanwhile, 90 leucite-reinforced ceramic sections (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein) of 6×6×4 mm^3 were cut and sintered according to the manufacturer's protocol. The cross sections of the ceramic sections that would serve as the bonding surface were ground with 280 grit SiC papers to produce marginal angles of 90° (Figure 2A2 and 2C3) or 60° (Figure 2B2). The permissible deviation of the marginal angle was ±3°.

After ultrasonic cleaning with deionized water (KQ-50B, Shumei, Kunshan, China), the abraded surfaces of the tooth sections were etched (30 seconds for enamel, 15 seconds for dentin) with 35% phosphoric acid gel (3M Oral Care, St. Paul, MN, USA), rinsed for 30 seconds with water spray, and dried with oil-free air. The abraded surfaces of ceramic sections were etched with 4.9% hydrofluoric acid gel (IPS ceramic etching gel, Ivoclar Vivadent) for 20 seconds, rinsed for 60 seconds, and air dried. Then the tooth sections with different marginal angles were bonded to the corresponding ceramic sections. For the tooth sections with a 75° marginal angle, a resin composite (Filtek Z350, 3M Oral Care) was applied incrementally on the dentin under the guidance of glass plates (Figure 2C2) to form two resin supports to facilitate the subsequent bonding between tooth and inlay. A dual-cured universal resin cement (Rely U200, 3M Oral Care) was mixed following the manufacturer's instructions and applied to the entire ceramic and tooth surfaces. The inner surfaces of the tooth and ceramic sections were pressed together with an axial load of approximately 0.5 kg, ensuring that the occlusal surface of the tooth section was in the same plane as the face of the ceramic section by using a glass plate (Figures 2A2, 2B2, and 2C3). To control the resin cement thickness, a single indicator paper with a thickness of approximately 50 μm was positioned at the periphery of the bonding surface near the dentin side. After removing excess cement, light curing was applied to each side of the specimen for 40 seconds with an LED-type light source (Bluephase, 800 mW/cm^2, Ivoclar Vivadent).

The bonded specimens were stored in artificial saliva for 24 hours at 37°C and then embedded (Figures 2A3, 2B3, and 2C4) in an auto-polymerizing acrylic resin (Struers). Then the bonded surfaces of all specimens were ground with SiC papers in a sequence of decreasing abrasive size (P280, P800, P1200, P2400, and P4000-grit) under water irrigation and highly polished with 3 and 0.04 μm abrasive particle solutions with felt cloths (Dac, Struers) on a dedicated instrument (Tegramin-30, Struers). Finally, the specimens were observed under an optical microscope (OM, BX51RF, Olympus, Tokyo, Japan) at 200×. The bonded interface remained intact and the measured interface width ranged from 30 μm to 80 μm.

Micro-Vickers Indentation Test

Micro-Vickers indentations were introduced on the enamel and ceramic portions of the polished specimens using a hardness tester (MVK-E, Akashi, Kanagawa, Japan) with 1 N load for 15 seconds in air, at distances of approximately 50, 100, 200, and 400 μm from the bonded interface edge to the center of the tip of the Vickers indenter (Figure 3). The diagonal of indentation was controlled to be parallel and perpendicular to the bonded interface. Ten specimens were chosen from each angle group, and eight indentations spaced at least 500 μm from each other were applied at four distances for each specimen. Then the specimens were observed under OM at magnification of 100×. The lengths of the two ends of the indentations were measured as indentation length (L1), and the longest lengths of the two ends of radial cracks running approximately parallel to the interface were measured as the indentation crack length (L2).

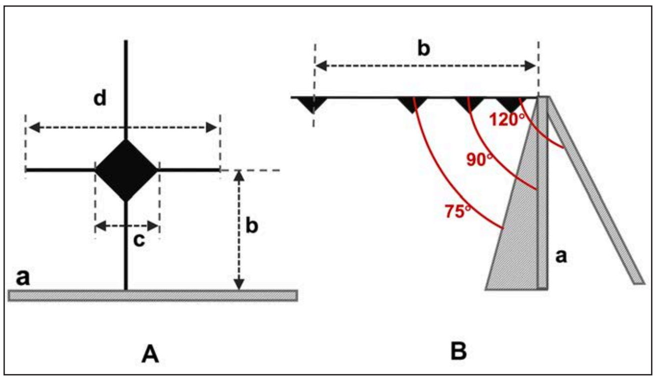

Figure 3. *Schematic diagram of the indentation test (A: vertical view, B: section view). Black diamond indicates the Micro-Vickers indentation; a: the bonded interface; b: the distance between indentation and bonded interface on occlusal surface (b=50, 100, 200, or 400 μm); c: the measured indentation length (L1); d: the measured indentation crack length (L2).*

Wear Tests

Reciprocating wear tests were conducted on the occlusal surface of specimens with ball-on-flat configuration by using a commercial tribometer (MFT-5000, Rtec-Instruments Inc, San Jose, CA, USA). Silicon nitride (SiN) balls with a diameter of 6.35 mm were used as the antagonists.[28,29] The tests were performed under simulated artificial saliva (A7990, Beijing Solarbio Science & Technology Co Ltd, China) lubrication at 25° room temperature. The testing parameters included a vertical load of 20 N, a sliding distance of 2 mm and a frequency of 1 Hz.[30,31] The occlusal contacts were marked with articulating paper to ensure that the displacement midpoint of the articulations was located at the bonded interface. A total of 5×10^4 cycles was performed, and three intervals of data analysis were employed after 5×10^2, 5×10^3 and 5×10^4 cycles. Eight tests were carried out for each cycle. Each wear scar was scanned using a white light interferometer (UP series, Rtec-Instruments Inc) operating in the vertical scanning mode equipped with the tribometer, and three-dimensional topography maps of the wear scars were reconstructed. Profiles of the wear scars were obtained from near the center of the scars and perpendicular to the bonded interfaces along the path of displacement. Taking the height of the unworn surface on both sides of the wear scar as a reference, the wear depths of the bonded interface area were calculated within the cement, the enamel, and the inlay material. For consistency, the locations of measurement for the enamel and inlay material were 30 μm from the bonded interface edge. Thereafter, representative specimens from each group were examined using scanning electron microscopy (SEM, INSPECTE, Czech Republic). The wear characteristics and mechanisms were analyzed from the wear-scar morphology.

Statistical Analysis

All data were analyzed with software IBM SPSS Statistics 20.0 (IBM, USA). A two-way analysis of variance (ANOVA) and Tukey multiple comparisons were used to compare the L1 and L2 measurements with different angles and distances from the bonded interface. A one-way ANOVA was performed to assess the differences in wear depth. The level of significance was defined at 0.05.

RESULTS

Indentation Crack Behavior

The results of L1 and L2 measurements are summarized in Figure 4. Representative micrographs of the indentations are shown in Figure 5.

On the tooth enamel surface, two-way ANOVA revealed that both L1 and L2 were significantly affected by the distance from the enamel/resin interface ($p<0.001$ for L1 and $p=0.001$ for L2) and the marginal angle ($p<0.001$ for L1 and $p=0.001$ for L2). Multiple comparisons among the means at the four distances showed that the L1 at

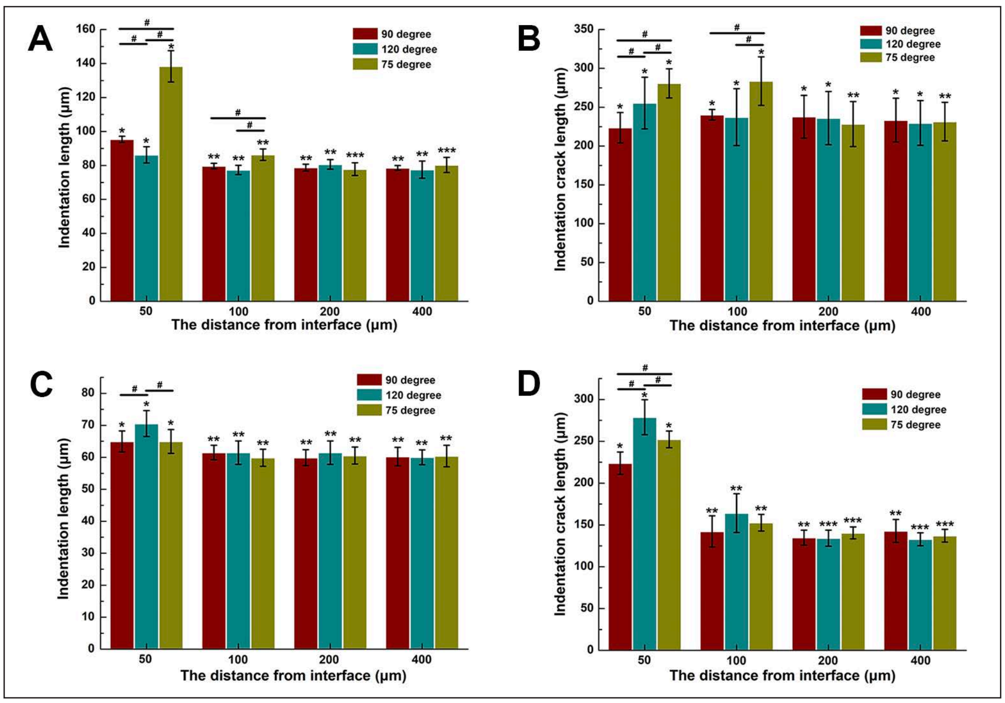

Figure 4. *Comparison of differences in indentation length (L1) and indentation crack length (L2) on tooth enamel (A, B) and ceramic (C, D) among the three groups. Same symbols (*,**,***) denote that there is no significant difference among different groups; # indicates there is significant difference between two groups at same measuring position; vertical error bars indicate the standard deviations.*

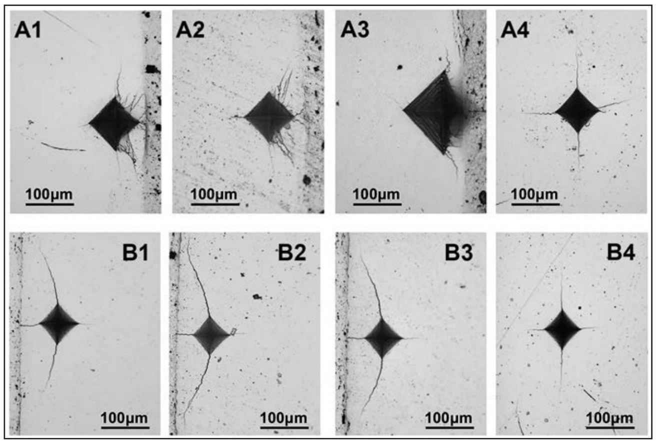

Figure 5. *Representative micrographs of the indentations and cracks in tooth enamel (A1-A4) and leucite-reinforced ceramic (B1-B4). (A1, B1): 50 μm-90° group; (A2, B2): 50 μm-120° group; (A3, B3): 50 μm-75° group; A4, (B4): 100 μm-90° group.*

a distance of 50 μm was the longest in each marginal angle group (p<0.001 for the 90° group, p=0.003 for the 120° group and p<0.001 for the 75° group). Among the three angles, the 75° group showed the biggest L1 and L2 (p<0.001) at the distance of 50 μm. The indentations for the 75° group were so large that they extended to the cement area, and the boundary of the cement area was not clear (Figure 5A3). In addition, the number of cracks was significantly greater (p<0.001) for the 50 μm distance. Besides radial cracks extending from the indentation corners, some lateral cracks were initiated from the indentation boundary, especially on the side flanking the cement (Figure 5A1).

On the ceramic surface, L1 and L2 were also affected by the distance from the enamel/resin interface (p<0.001 for L1 and L2) and the marginal angle (p=0.006 for L1 and p<0.001 for L2). Multiple comparisons indicated the largest L1 (p=0.008 for the 90° group, p<0.001 for the 120° group, and p=0.003 for 75° the group) and L2 (p<0.001 for all three groups) resulted from indentations placed 50 μm from the interface (Figures 4C and 4D). Among the three groups, the 120° group exhibited the largest L1 (p=0.002) and L2 (p<0.001). Radial cracks were initiated at the indentation corners and propagated parallel to the indentation diagonals and bonded interface within the ceramic. For the 50 μm indentation distance, the cracks gradually approached the interface with extension (Figure 5B1).

Wear Behavior

A comparison of typical vertical profiles and wear depths is presented in Figure 6. After 5×10^2 cycles, the vertical profiles exhibited a discontinuity in the vicinity of the bonded interface (Figure 6A1). Wear of the enamel exceeded that of the inlay regardless of the marginal angle. The 120° group experienced the greatest wear in the enamel (p=0.008), cement (p<0.001) and inlay material (p=0.010) among the three marginal angles (Figure 6A2), and the wear depth in the enamel of the 75° group exceeded that of the 90° group (p=0.038). At the next sliding contact interval (5×10^3 cycles), the wear scars appeared relatively smooth, with no abrupt discontinuities (Figure 6B1). There was no significant difference (Figure 6B2) in the extent of wear among the three groups (p=0.147 for enamel, p=0.249 for cement, and p=0.761 for ceramic) or among enamel, cement, and ceramic portions at the interface area (p=0.663 for the 90° group, p=0.359 for the 120° group, and p=0.288 for the 75° group). With further progression of the sliding contact (5×10^4 cycles), wear of the inlay increased rapidly and exceeded that of the cement and adjacent enamel (Figure 6C1). Interestingly, there was no significant difference (Figure 6C2) in the extent of wear in the bonded interface among the three marginal angle groups (p=0.659 for enamel, p=0.300 for cement, and p=0.178 for ceramic).

Wear Morphology

Micrographs documenting the morphology of typical wear scars after 5×10^2 and 5×10^4 cycles are shown in Figure 7 and Figure 8. After 5×10^2 cycles of sliding contact, the extent of damage in the bonded interface area was distinctly a function of marginal angle. The bonded interface of the 90° group exhibited the highest integrity overall. Only some small chips developed on the ceramic edge, and the enamel-cement interface appeared intact. For the 120° group, the width of the wear scar at the bonded interface was wider, suggesting a scuffing motion at the interface. Large cracks and exfoliation were evident on the ceramic edge (Figure 7B). Nevertheless, the interface between the cement and enamel still appeared to remain intact. For the 75° group, chipping and cracks were apparent both on the ceramic edge and in the adjacent tooth enamel (Figure 7C). The bond integrity between the enamel and cement appeared degraded as well.

With an increase to 5×10^3 cycles, the bonded interface appeared to be intact, with minimal evidence of damage, except for a few cracks concentrated in the ceramic just adjacent to the interface and not dependent upon the marginal angle (image not shown).

With an increase to 5×10^4 cycles, similar wear morphologies were found in the three groups. Although obvious cracks were identified in the ceramic near the bonded interface, the enamel-cement and cement-ceramic interfaces appeared intact (Figure 8).

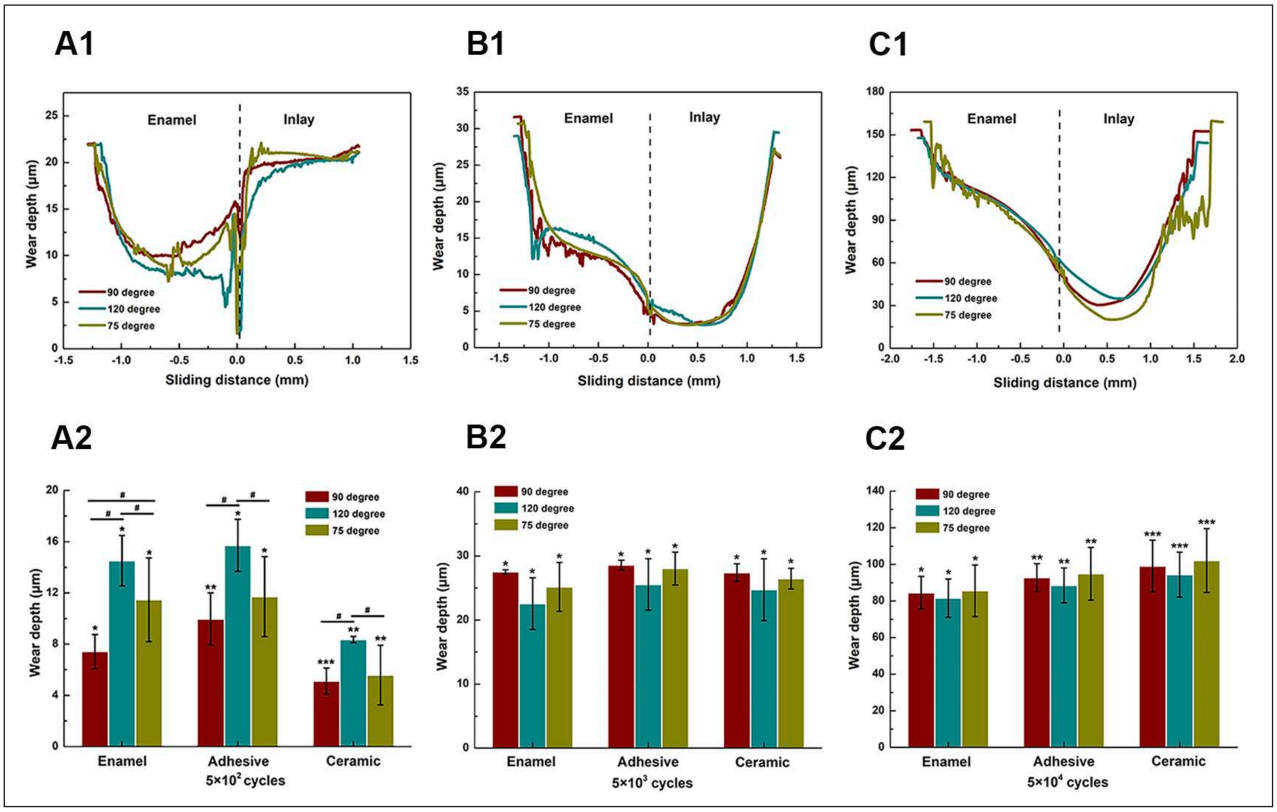

Figure 6. *Comparison of the typical vertical profiles and wear depths for the three marginal angle groups after different testing increments. (A1, A2): 5×102 cycles; (B1, B2): 5×103 cycles; (C1, C2): 5×104 cycles. Black dotted lines in A1-C1 indicate the bonded interface. Same symbols (*,**,***) denote that there is no significant difference in wear depth among tooth enamel, cement, and inlay material for each group; # indicates there is significant difference in wear depth between two groups; vertical error bars indicate the standard deviations.*

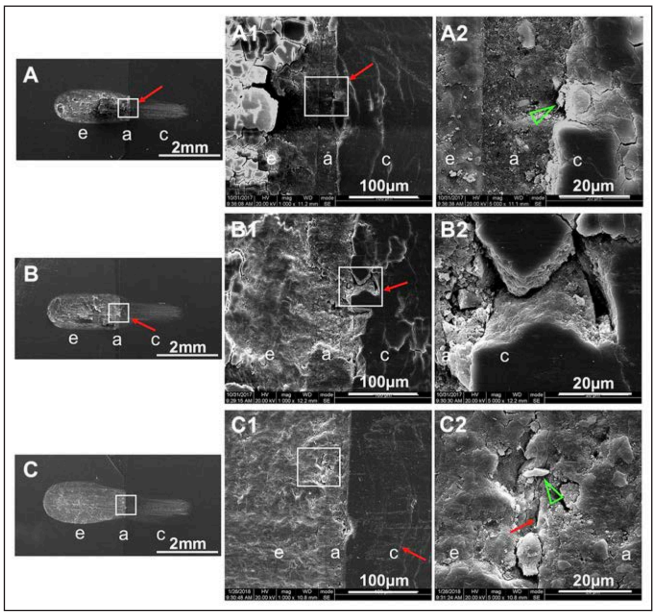

Figure 7. *Representative SEM micrographs of the worn surfaces after 5×102 cycles. (A): 90° group; (B): 120° group; (C): 75° group; white squares outline the bonded interface in wear scars and are shown in right images at higher magnification; e: enamel, a: cement, c: ceramic; arrows point to cracks; triangles indicate chipping.*

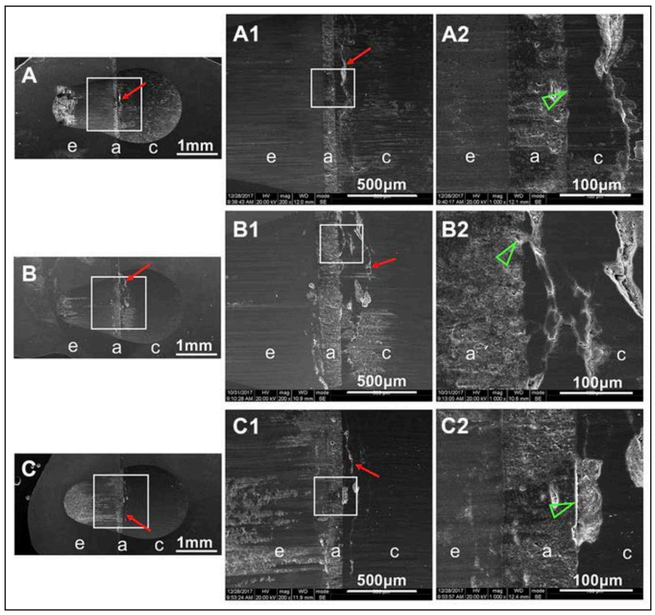

Figure 8. *Representative SEM micrographs of the worn surfaces after 5×104 cycles. (A): 90° group; (B): 120° group; (C): 75° group; white squares outline the bonded interface in wear scars and are shown in right images at higher magnification; e: enamel, a: cement, c: ceramic; arrows point to cracks; triangles indicate chipping.*

DISCUSSION

The present work studied the effect of cavity preparation design on the extent of wear and the damage mechanisms in ceramic inlay bonded interfaces. The results obtained showed that the wear depth and surface morphology varied as a function of the marginal angle at the initial stage of wear, while no significant difference was found in the later stages. Therefore, the null hypothesis was partially rejected.

In the indentation test, indentation cracks were dependent on the distance of the indentation from the interface, a finding in agreement with previous studies.[23,24] To some extent, the direction of crack extension reflects the weak area of the restoration. When the indentation was introduced near the bonded interface, more cracks were generated and/or the cracks were longer, thereby suggesting that the interface area is most vulnerable to damage induced by cyclic sliding contact. Similar to the results of the indentation damage test, the wear depth was most severe at the interface area and decreased with increasing distance from the interface. Therefore, to minimize marginal deterioration of inlay restorations, clinicians should be vigilant to avoid placing centric occlusion on the bonded interface if possible.

Apart from the importance of distance, the characteristics of cracks resulting from the indentations were also dependent on the tooth marginal angle. According to the work of Dejak and others,[21] the stress intensity factor for cracks increased and the critical stress causing fracture of the restoration decreased with a reduction in the edge angle of inlays. Similarly, Nishide and others[3] showed that when the ceramic marginal angle changed from 90° to 60° to 45°, the critical stress required for fracture decreased to 1/3 and 1/5 of the original values. Indeed, the L1 and L2 for the 120° group (with a 60° ceramic edge angle) near the bonded interface were significantly greater than those of 90° group and 75° group (both with 90° ceramic edge angle). At the early stage of sliding contact, the contact area between the bonded interface specimen and the antagonist ball was essentially a ball-on-flat configuration. As such, the contact stress was higher at the beginning of the cyclic wear testing. Numerous cone cracking or inner cone cracking modes appeared in the ceramic structures near the bonded interface, particularly in the 120° group, as also shown in the study of Zhang and others.[32] The cracks intersected with each other or combined with the more damaging radial crack that can initiate from either the top or bottom surface of the brittle materials, especially with the thinner ceramic on the edge, resulting in the formation of large irregular peeling fragments (Figure 7B). With the loss of ceramic support, the adjacent cement and enamel were exposed and underwent accelerated wear as a result of sliding contact.[3] This might be the cause of the significantly larger wear depth of the bonded interface of the 120° group compared to the others.

A bonded interface involves enamel supported by a foundation of dentin. When compared to enamel, dentin has lower hardness and elastic modulus and greater potential for stress relief.[27] When subjected to concentrated force, dentin can act as a damper to reduce the stress by viscous processes, which increases the resistance of enamel to brittle fracture. For the 75° group, the tooth margin had an acute angle, resulting in less enamel structure surrounding and supporting the indentation and a lack of the buffer action of inner dentin.[22] In this condition, the enamel surface collapsed under the indentation stress, resulting in a significantly larger indentation and numerous microcracks at the indentation boundary (Figure 5A3). Under cyclic sliding contact, small bundles of enamel rods underwent crushing, resulting in brittle fracture and chipping (Figure 7C). Without the support of the enamel, wear on the cement and the ceramic inlay were accelerated. Accordingly, the 75° group showed a larger wear depth than the 90° group at the initial stage of sliding contact.

Although both the 120° and 75° groups experienced more severe damage on the bonded interface area in the early stage of sliding contact, there was no significant difference in wear depth and damage characteristics at the later stages. This change in behavior with more prolonged contact could be the result of two factors. Firstly, the contact area between the wear scar and the antagonist ball increased, resulting in a decrease in contact stress. Secondly, due to its higher modulus, the ceramic inlay bears a larger portion of the contact load at the bonded interface area,[33,34] protecting the residual dental tissue and facilitating accelerated wear relative to the tooth enamel.[25] With continuation of the sliding contact, wear in the ceramic gradually exceeded that in the enamel, resulting in an uneven wear surface. Based on the history of the wear-scar morphology shown in Figure 9, the marginal angle of the dental tissue gradually increased and, with progression of the sliding contact, exceeded 90°. The ability to bear stress increases with increasing marginal angle.[21,22] Indeed, the SEM analysis also showed that there was no obvious damage in the nearby enamel at the later stage for the three groups. On the contrary, the marginal angle of the ceramic inlay decreased gradually with wear, resulting in a degradation of its load-bearing ability. As shown in Figure 8, all three groups exhibited obvious cracks and chipping of the ceramic adjacent to the bonded interface at the later stages of the evaluation.

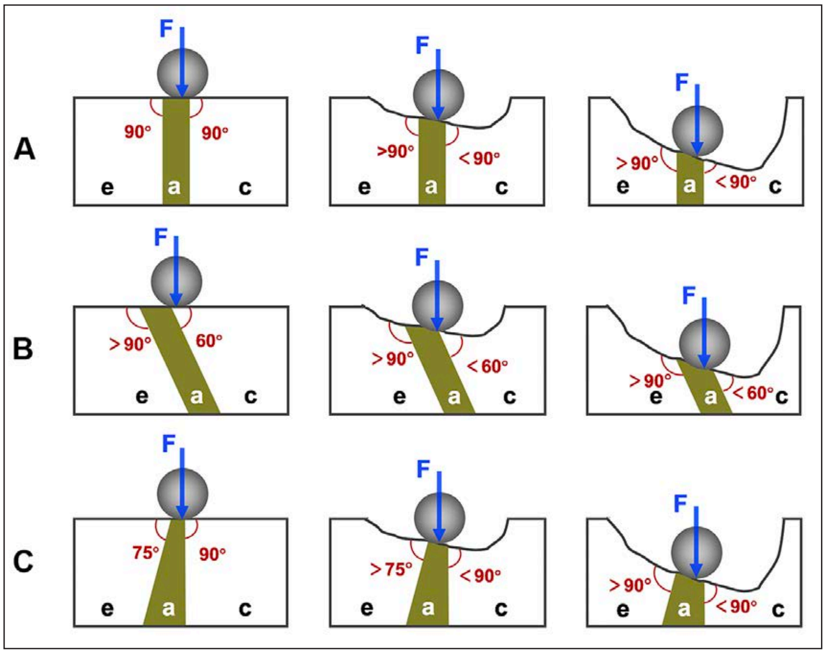

Figure 9. *Schematic representation of the evolution of wear at the ceramic inlay bonded interface with continuing sliding contact (number of cycles increases from left to right). (A): 90° group; (B): 120° group; (C): 75° group; e: enamel, a: cement, c: ceramic.*

Overall, results of the evaluation indicated that minimally invasive preparation designs with either larger or smaller marginal angles than conventional preparations experienced more serious interface damage in the early stages of function. However, no significant difference was found in wear damage behaviors at the later stage. Under very controlled conditions, the wear depth of bonded interface was about 20-30 μm after 5×10^3 cycles of sliding wear in this study, which is roughly equivalent to about 1 year of chewing movement in the mouth.[35] This means that the influence of tooth marginal angle on the integrity of the bonded interface might last less than 1 year. Of course, more serious interface damage in the early stage could facilitate the accumulation of plaque and pigment, increasing the risk of other complications.[36,37] Therefore, for inlay cavities with unconventional tooth marginal angles or axial walls located at the cusp inclination, the authors recommend that clinicians use a distributed occlusion contact in order to reduce contact stress and monitor the bonded interface area more frequently at the initial stage.

Although care was taken to study the effect of cavity preparation design on the extent of wear and damage mechanisms at bonded interfaces in a clinically relevant manner, it is important to recognize the differences between the test conditions and the clinic. Due to the complexity and uncontrollability of the oral environment, the bonded interfaces in this study were prepared with specific geometry and investigated under very controlled conditions, which could act as an important predictive tool for clinical performance.[38] However, the influence of variations in tooth anatomic form, pH, temperature, bacterial biofilm, and other challenges is relatively unknown. In addition, only specific tooth marginal angles were analyzed in this experiment, which was a preliminary investigation on the effect of tooth marginal angle on interface damage. The correlation between the marginal angle and the damage extent of the bonded interface and the critical angle affecting the damage behavior need to be further explored. Considering these limitations, further studies with more narrow grouping are currently underway to explore the importance of these additional factors.

CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn:

1. Crack extension and wear damage within the vicinity of the bonded interface were significantly greater than those further away from the interface. The interface area is more vulnerable to damage induced by cyclic sliding contact.
2. Indentation crack resistance of the inlay bonded interfaces was significantly dependent on the marginal angle. In comparison to the 90° conventional preparations, the 120° group exhibited longer indentation cracks on the ceramic edge, whereas the 75° group showed significantly larger indentations on the enamel edge.
3. Under cyclic sliding contact, minimally invasive preparations with 120° and 75° marginal angles underwent more extensive damage at ceramic inlay

bonded interfaces in the initial stage of function but showed comparable damage behavior to the 90° group at the later stages.

Acknowledgment

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Regulatory Statement

The experimental procedure involving teeth was approved by the Research Ethics Committee of Sichuan University West China College of Stomatology (WCHSIRB-D-2016-046) and was in accordance with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Both the collection and use of teeth were performed with the informed consent of all the patients.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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