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Reliability Testing of Indirect Composites as Single Implant Restorations

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Abstract

Purpose: To investigate the reliability and failure modes of indirect composites as single-unit implant crowns.
Materials and Methods: Thirty-eight custom-milled titanium alloy locking-taper abutments were divided into two groups (n = 19 each), and crown build-up of a mandibular molar was accomplished using two indirect composite systems (Ceramage, Shofu, Kyoto, Japan; Diamond Crown, DRM, Branford, CT). Three crowns of each material were loaded until failure for determination of the step-stress profiles. Reliability testing started at a load 30% of the mean load to failure and used three profiles with increasing fatigue loading (step stress). Weibull curves with 300 N stress and 90% confidence intervals were calculated and plotted using a power-law relationship. Weibull modulus "Beta" and characteristic strength "Eta" were identified, and a contour plot was used (Beta vs. Eta) for examining differences between groups. Specimens were inspected in polarized light and scanning electron microscope for fracture analysis.
Results: Use level Weibull probability showed fatigue being a damage factor only for the Ceramage group ($\beta = 3.39$) but not for the Diamond Crown group ($\beta = 0.40$). Overlap in the confidence bounds resulted in no statistical difference. Irrespective of composite system, fracture initiated in the region immediately below the contact between the indenter and the cusp, with the crack propagating toward the margins of cohesive failure.
Conclusions: No significant differences were observed in life and Weibull probability calculations for Ceramage and Diamond Crown veneered onto Ti alloy abutments. Failure modes comprised composite veneer chippings.

Ceramic materials have long been used for the restoration of teeth, as ceramic can imitate tooth structure in color, translucency, and response to different lighting sources.[1] With the increasing number of dental implants being placed, the restorative techniques used for conventional prosthodontics have been adapted, and the restoration of single implants is usually completed using metal ceramic (MC) crowns.[2,3] MC crowns are traditionally manufactured by a powder build-up porcelain layered and fired over the cast metal core and then cemented or screwed to the implant abutment. Regardless of restoration material, implant-supported restorations present higher complication rates (veneer fracture, screw loosening) compared to conventionally supported prostheses.[4]

Despite substantial improvements in the mechanical properties of all-ceramic materials, failure rates are also significantly higher compared to MC in implant-supported reconstructions.[5,6] Hence, MCs are still considered the gold standard in restorative dentistry; however, properties such as high abrasion to the opposing dentition, repair limitations, brittleness, and hardness are considered disadvantages. These complications have led to the search for materials that can be bonded directly to the supporting metallic framework,[7–10] such as resin composites. The second generation indirect composites were introduced to the market during the 1990s,[11] and the resulting improved mechanical properties compared to their predecessor encouraged their use in the fabrication of full-coverage single unit crowns, inlays, onlays, and veneers.[12]

The use of composite resins over metallic structures has been a topic of investigation due to concerns regarding the adhesive potential to different metal substrates and the stability under intraoral conditions. In an attempt to increase the adhesion to metallic frameworks, addition of loops and beads for mechanical interlocking, airborne particle abrasion to increase the surface area available,[13] mechanical interlocking, and increased chemical adhesion due to silica particle residues on the metallic substrate[13,14] have been suggested. Chemical methods such as electroplating, ion coating, and different metallic and polymeric primers have also been shown to positively influence bond strengths of composites to metals.[15-17]

Recently, several resin-based composites with different formulations bonded to either chemically treated or airborne particle abraded Ti-6Al-4V were subjected to microtensile bond strength testing and presented promising results, suggesting their potential as veneer materials when directly applied over Ti alloy.[18] The clinical application of indirect composite systems directly bonded to Ti alloy abutments has been described as an alternative technique for restoring single-unit implants, known as the Integrated Abutment Crown™ (IAC™). In essence, the implant abutment and the crown material are one unit (no cement or screw is used), to be locking-taper connected (without a screw) to the implant well.[19] Besides the acceptable esthetic appearance of recently developed composites, a potential advantage is the possibility of direct repair, should chipping occur.[19] Although several publications have addressed the mechanical behavior of all-ceramic and MC materials as implant restorations,[20-22] the literature concerning directly bonding composite restorative materials for implant restorations has not been thoroughly addressed to date. The objective of this investigation was to evaluate the reliability and failure modes of two indirect composite resin systems with different chemistry applied directly to Ti alloy abutments with a locking-taper connection. The null hypothesis tested was that there would be no difference in B10 life (which describes the time, here cycles, at which X% of the units in a sample size will have failed), Weibull probability calculations, or failure modes whenever two composite systems are subjected to R-ratio accelerated step-stress fatigue test.

Materials and methods

A total of 38 titanium alloy (Ti-6Al-4V) locking-taper abutments (Bicon LLC, Boston, MA) were used. The abutments were industrially milled and airborne particle abraded (Al_2O) by a technician, resulting in similar thicknesses for composite veneering. After preparation they presented a dome-shaped configuration, with a 1-mm-deep chamber along the cervical area. The two materials used for crown fabrication are listed in Table 1.

For crown fabrication, all abutments were airborne particle abraded prior to the application of the composites. To avoid roughness inclusions on the locking-taper connection area, the stem of each abutment was protected with wax during blasting procedures. This procedure was accomplished using 50-μm aluminum oxide particles (80 psi at 1 cm distance, perpendicular to the long axis of the surface).

Table 1 Indirect composite systems used for crown fabrication and their composition

Material	Manufacturer	General composition (as supplied by the manufacturer)
Ceramage	Shofu; Kyoto, Japan	Zirconium silicate featuring a progressively fine structural filling of more than 73% by weight of microfine ceramic particles in an organic polymer matrix
Diamond Crown	DRM Research Laboratories; Branford, CT	Phenolic-epoxyne matrix glass-ceramic sílica filled (80% filler by weight) with semicrystalline microstructure

Prior to composite buildup, the abutments were placed in an ultrasonic bath and air dried. Then, incremental composite layers were veneered according to the manufacturer's instructions (Table 2). A silicon impression of the mandibular molar crown's desired anatomy was used to guide incremental resin buildup and standardize the crown's final contour. The composite systems were light cured (DiamondLite Fotokur F/X Laboratory Halogen Light Booth, DRM, at 500 mW/cm^2) according to the manufacturer's recommendations. A final curing cycle was performed after complete resin buildup. After 48 hours, finishing and polishing steps included the use of carbide burs in a slow-speed handpiece, followed by silicon brushes, rubber tips, and polishing paste (CompoShine, Shofu, Kyoto, Japan) applied with a muslin buff. The specimens were allowed to age in water for 30 days at room temperature prior to testing.

The fabrication of a standardized positioning apparatus for the testing machine was accomplished using PVC tubing and a silicone matrix with the final crown embedded (occlusal surface down) and its abutment connecting taper exposed to orient its axial position. The tubing was sectioned and positioned over the silicone key containing the implant/abutment assembly in the center. Then, self-curing acrylic resin (Orthodontic resin, Dentsply Caulk, Milford, DE) was poured to produce a stable base containing the Ti-6Al-4V locking-taper connection implant (3.5-mm diameter, 8-mm long, Bicon LLC). This assembly allowed the crowns to be seated on the locking-taper implants and facilitated positioning of the specimens at a universal testing machine (Model 800R, Test Resources, Inc., Shakopee, MN).

Nineteen crowns of each material were fabricated. Three crowns of each material were loaded with a flat indenter at one of the four cusps at a 1 mm/min crosshead speed until fracture. Load versus displacement curves were recorded for each

Table 2 Manufacturer's instructions for crown buildup

Ceramage	Diamond Crown
Aluminum oxide airborne particle abrasion blasting (50 μm @ 80 psi)	Aluminum oxide airborne particle abrasion blasting (50 μm @ 80 psi)
Ultrasonic bath (ethyl alcohol) for 12 minutes	Ultrasonic bath (ethyl alcohol) for 5 minutes
Air dry	Air dry
Apply a fine layer of primer and wait for 45 seconds	Apply metal coupler (2 to 5 layers) and oven dry (250°F) for 5 minutes (no vacuum)
Apply preopaque layer; light cure for 3 minutes	Opaque (powder and liquid mix) applied over abutment; oven dry (250°F) for 5 minutes under vacuum
Apply dentin resin; light cure for 3 minutes	Apply Ceramo coupler and repeat opaque application until all abutment is covered with opaque
Apply body resin; light cure for 5 minutes	Check for opaque coverage; if ok, apply modeling liquid and light cure for 2 minutes
Light cure the bulk of the restoration for five cycles of 5 minutes	Apply opaque resin and light cure for 4 minutes
Apply incisal resin and light cure for 5 minutes	Apply body resin and light cure for 4 minutes
Finishing and polishing procedures	Apply incisal resin and light cure for 4 minutes
	Finishing and polishing procedures

specimen, so the mean load to failure for each material could be used in determining step-stress profiles for reliability testing.[23] The reliability testing consisted of testing the remaining specimens at step-stress levels for timely fracture and reliability calculation. Load profiles started at a load 30% of the mean load to failure. Three profiles were designed as mild, moderate, and aggressive, with the number of specimens assigned to each group in approximate ratios of 3:2:1, respectively.[23] These profiles are named based on their stepwise increase at which the specimen will be fatigued until a certain level of load. Therefore, specimens assigned to a mild profile will be cycled longer to reach the same load of a specimen assigned to the aggressive profile. All cyclic testing was performed in R-ratio fatigue mode (indenter does not leave specimen surface)[24] with a flat indenter. Both specimen and indenter were submerged in water, and the testing was conducted at room temperature.

Based upon the step-stress distribution of the failures, use level Weibull probability curves (probability of failure vs. cycles) with 300 N use stress and 90% confidence intervals were calculated and plotted (Alta Pro 7, ReliaSoft, Tucson, AZ) using a power-law relationship to identify whether fatigue is a damage factor accelerating material failure.[5,25-27] BX life calculation at 10% failure rate and 300 N load considering number of cycles as the output was performed. Weibull distribution fit was calculated for both groups by computer software (Weibull 6++, Reliasoft). Weibull modulus Beta (β) and characteristic strength Eta (η) (63.2% of the specimens would fail up to the calculated "η") were identified, and a contour plot was used (β vs. η) for examining differences between groups.

Table 3 BX life calculation at 10% failure rate and 300 N load. Number of cycles was considered as the output using Fisher matrix method for confidence intervals calculation. No statistical difference was found as a result of overlap between upper and lower limits of both groups

10% failure rate @ 300 N	Ceramage	Diamond
Upper	5.07E $\times$ 10^{04}	1.03E $\times$ 10^{06}
Cycles	3.85E $\times$ 10^{04}	8.19E $\times$ 10^{04}
Lower	2.92E $\times$ 10^{04}	6490

The specimens were evaluated at the completion of each fatigue step for crack/fracture status. Failed specimens were first inspected in polarized light (MZ-APO stereomicroscope, Carl Zeiss Micro Imaging, Thornwood, NY) and subsequently gold sputtered (Emitech K650, Emitech Products Inc., Houston, TX) followed by fractographic analysis using a scanning electron microscope (SEM) (Model 3500S, Hitachi Ltd., Osaka, Japan). Criteria used for failure were delamination (abutment exposure), or cohesive fracture within the composite (chipping).[28]

Results

The average single load to fracture strength for Ceramage specimens was 1099 ± 257 N and for the Diamond Crown specimens, 1155 ± 284 N. Use level Weibull probability showed fatigue being a damage factor for Ceramage ($\beta = 3.39$), but not for Diamond ($\beta = 0.40$). The β value (called the Weibull shape factor) describes failure rate changes over time ($\beta < 1$: failure rate decreases over time, commonly associated with "early failures" or failures that occur due to egregious flaws; $\beta \sim 1$: failure rate does not vary over time, associated with failures of a random nature; $\beta > 1$: failure rate increases over time, associated with failures related to damage accumulation).[27,29,30]

Table 3 depicts BX (10% failure rate) values for a 300 N load. Confidence bounds (2-sided and 90% confidence level) were calculated using the Fisher matrix method. No statistical difference between groups was observed as a result of overlap between upper and lower limits values.[29] Broader confidence intervals, however, can be noticed in the Diamond Crown group. A Weibull probability contour plot (Fig 1) showed overlap between both groups. Characteristic strength η values were 807.16 and 807.87 for Ceramage and Diamond, respectively.

Fracture analysis through SEM showed that, irrespective of composite system, the failure initiated in the region immediately below the contact between the indenter and the cusp.

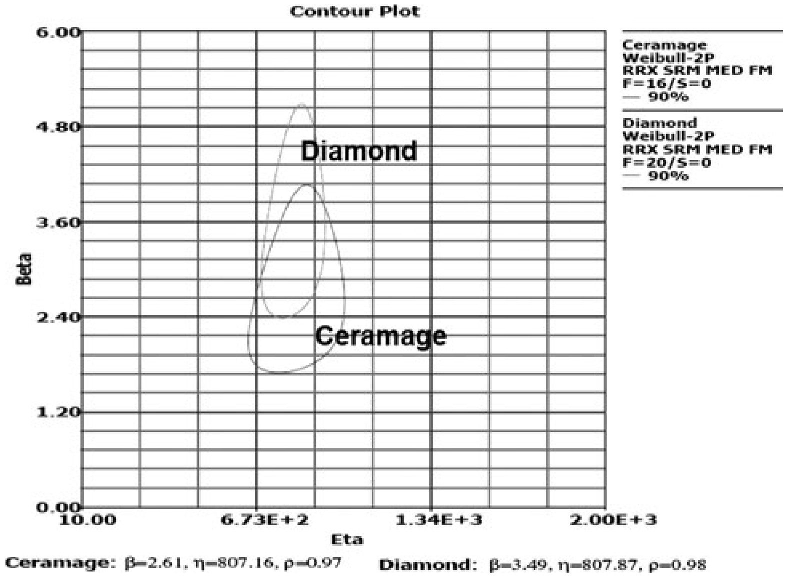

Figure 1 Contour plot (β vs. η) of groups Ceramage and Diamond. Note overlap between groups demonstrating no statistical difference. Characteristic strength η values are similar for both restorative systems.

At this region, crack initiation propagated toward the margins of cohesive failure. Crack growth direction was confirmed by hackle lines in both materials (Figs 2 and 3).

Discussion

The objective of the present study was to investigate the mechanism of failure and reliability of two composite materials used for the IAC™ concept. The fracture strength of IACs™ fabricated with either Diamond Crown or Ceramage did not reach statistical significance ($p > 0.85$). This finding could be related to the fact that both systems are considered second generation indirect composites, and likely present similar mechanical properties.[11,31,32] Although the compositions of Diamond Crown and Ceramage are different, they did not influence materials' response to fatigue. B10 life and Weibull probability calculations showed no significant difference between the groups. The higher confidence bounds observed for Diamond Crown may be related to differences in chemical formulation between the materials. The fatigue loading resulted in similar fracture modes and crack propagation between the groups including composite chips that originated from the contact area, without exposure of the underlying abutment. Although indirect composites may be fractographic unfriendly, telltale markers indicating fracture origin, and direction of fracture propagation allowed a qualitative analysis, which is in agreement with a previous study of indirect composite bar-shaped specimens.[33]

Despite the use of the classic R-ratio fatigue, instead of mouth-motion (indenter contacts, applies the load, slides 0.5 mm, and lifts off the specimen surface), the fracture modes observed in our imaging results are in agreement with those reported in a retrospective cohort study of single implants restored with IACs™ and followed up to 29 months. Out of 71% of crowns restoring posterior areas (n = 59), only one minor cohesive failure was detected during the first year, and refinishing procedures allowed the crown to continue in function uneventfully for the remainder of the study. The survival rate was 98.7%, and color stability did not seem to be an issue affecting esthetics.[34] Similar failure modes and reliability have been reported for R-ratio fatigue and uniaxial fatigue (indenter contacts, applies the load, and lifts off the specimen surface).[24]

Although MC crowns are the most widely used modality of full-coverage restorations, some of their inherent properties such as high abrasion and brittleness have been the driving forces behind the search for alternative materials for the same purpose. Recent improvements in composition and monomer-to-polymer conversion rates have brought claimed advantages such as improved wear resistance and esthetics along with increased bonding to tooth and metallic substrates.[31,35] The ultimate strength values were high (average 1128 N), an indication of enough resistance under masticatory function where loads usually do not exceed 700 N.[36,37] In addition, it is yet to be confirmed clinically, but chewing simulations comparing several composites to glass ceramic as materials for implant-supported restorations showed significantly lower peak vertical and transverse forces transmitted at the peri-implant level for the former materials.[38]

The accelerated life-testing method for reliability used in this investigation has been extensively employed in the materials engineering field for determination of reliability of materials, components, and assemblies.[23,39] Reliability is defined as the probability that a device will perform its intended function during a specified period of time under stated conditions, without failure. This approach yields more information for a given test time than normally would be possible under the intended use loads, but should be used with caution to avoid introducing failure modes not observed in normal use. The primary purpose of such a test is usually related to life

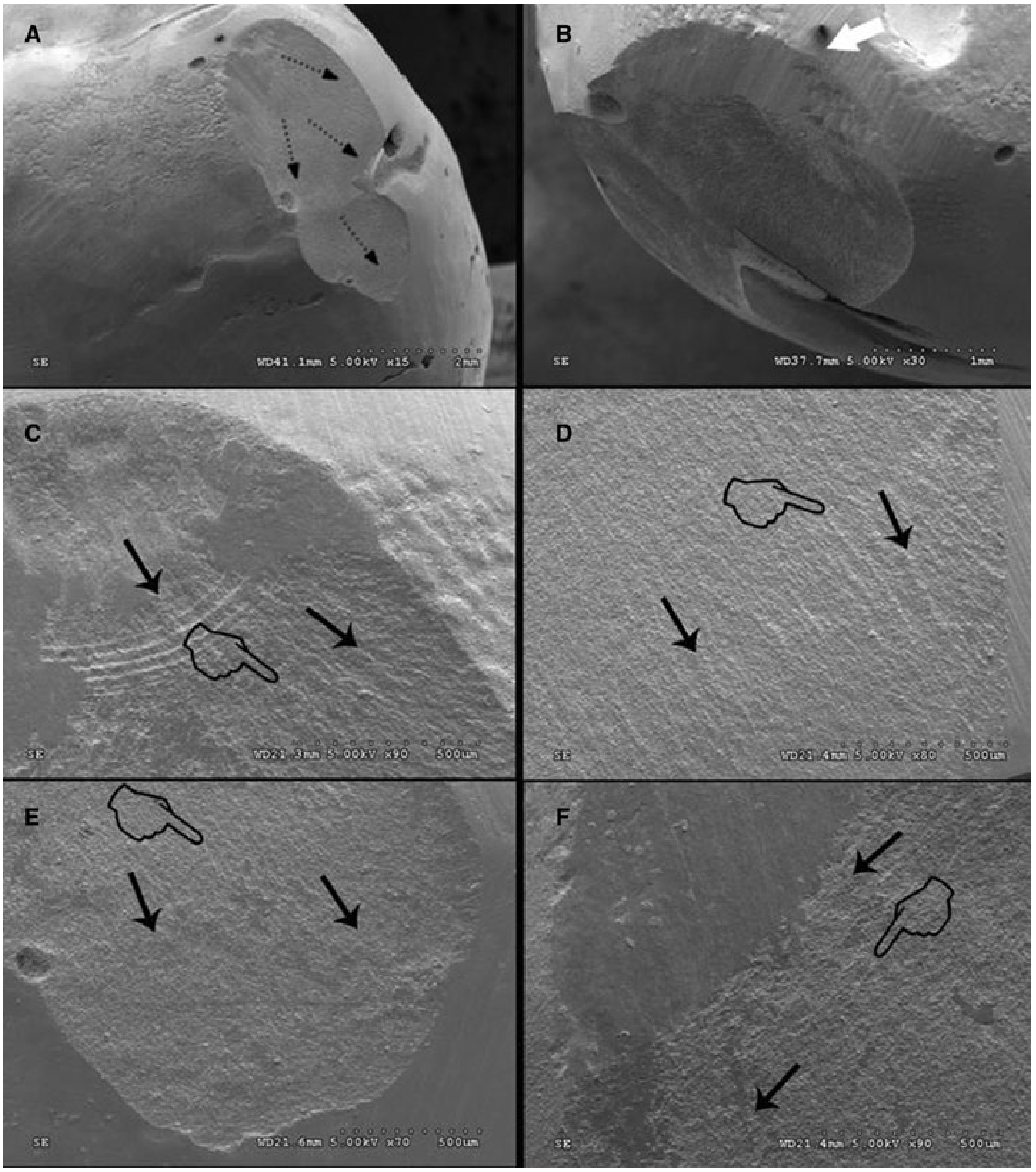

Figure 2 SEM micrographs of failed Ceramage crown after R-ratio fatigue. (A) Proximal view of chipped composite and direction of crack propagation (dotted arrows). (B) Occlusal view shows the depth of cohesive failure and indented area (white arrow) as the failure initiation site. (C) to (F) Magnifications of dotted arrow areas presented in (A) indicate crack front direction toward the margins of cohesive failure (arrows). Discrete fractographic markings depicted by hackle lines (pointers), confirm these findings.

estimation and problem/weakness identification (or confirmation) and correction of the subject in question.[23,39] Clinically, composite cohesive fractures without abutment exposure can be translated into easier chairside repair and repolishing procedures, unlike all-ceramic and porcelain-fused-to-metal restorations, where fractures often may require the fabrication of a completely new crown due to limitations in repair capabilities; however, it should be noted that long-term clinical assessment of composite systems veneered onto Ti alloy abutments is needed.

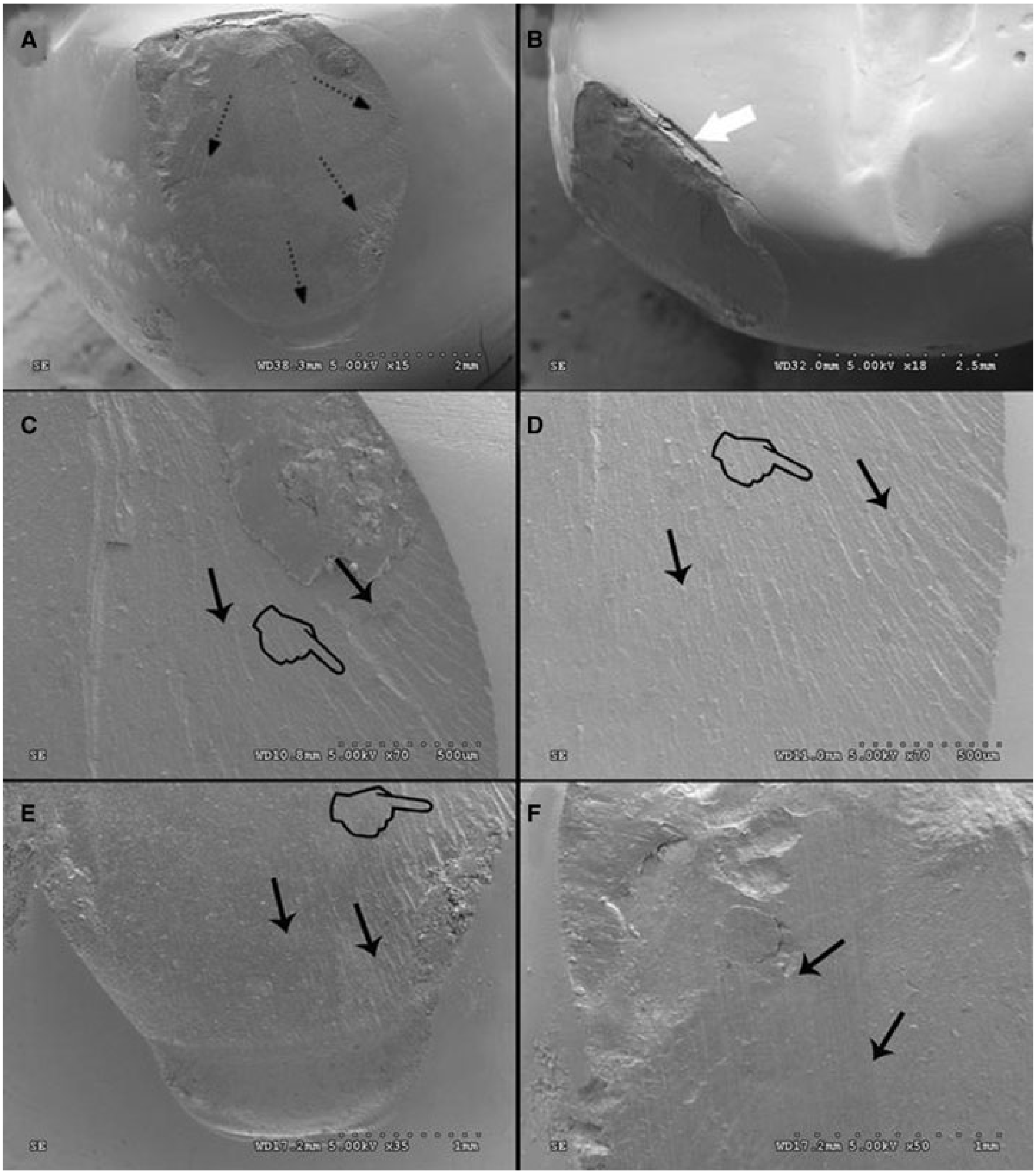

Figure 3 Representative SEM micrographs of composite chipping in a Diamond Crown fatigued specimen. (A) Dotted arrows depict crack front direction toward the marginal borders of cohesively failed composite. (B) Occlusal view shows the depth of chipped composite and failure initiation site, that is, indented area (white arrow). (C) to (F) Magnified dotted arrow areas shown in (A), crack front path (arrows) and its hackle lines (pointers).

Conclusion

There were no significant differences in BX (10%) life and Weibull probability calculations for Ceramage and Diamond Crown veneered onto titanium alloy abutments. Failure modes were similar for both composite systems and representative of clinically failed restorations. Thus, our postulated null hypothesis should be accepted.

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