Failure Analysis of Ceramic Clinical Cases Using Qualitative Fractography

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Purpose: To educate dental academic staff and clinicians on the application of descriptive (qualitative) fractography for analyses of clinical and laboratory failures of brittle materials such as glass and ceramic. ***Materials and Methods:*** The fracture surface topography of failed glass, glass fiber–reinforced composite, and ceramic restorations (Procera, Cerestore, In-Ceram, porcelain-fused-to-metal) was examined utilizing a scanning electron microscope. Replicas and original failed parts were scrutinized for classic fractographic features such as hackle, wake hackle, twist hackle, arrest lines, and mirrors. ***Results:*** Failed surfaces of the veneering porcelain of ceramic and porcelain-fused-to-metal crowns exhibited hackle, wake hackle, twist hackle, arrest lines, and compression curl, which were produced by the interaction of the advancing crack with the microstructure of the material. Fracture surfaces of glass and glass fiber–reinforced composite showed additional features, such as velocity hackle and mirrors. The observed features were good indicators of the local direction of crack propagation and were used to trace the crack back to an initial starting area (the origin). ***Conclusion:*** Examples of failure analysis in this study are intended to guide the researcher in using qualitative (descriptive) fractography as a tool for understanding the failure process in brittle restorative materials and also for assessing possible design inadequacies. *Int J Prosthodont 2006;19:185–192.*

Failure analysis is the investigation of why a component, structure, or system fails to perform a desired function. Fracture is the cause in many instances. The failure analysis includes examination of a fractured component to investigate the circumstances surrounding a failure event, with the expectation of eventually elucidating the cause of failure, whether it was a result of design deficiency, material deficiency (fabrication process), or in situ stress–induced conditions. Existing defects in restorative dental materials introduced during processing, machining, or resulting from in-service conditions (eg, wear, impact) represent structural weaknesses from which the fracture process may start. Intraoral clinical failures such as fractures typically will arise during chewing or nighttime parafunctions such as bruxism. Fractography encompasses the examination of fracture surfaces that contain features resulting from the interaction of the advancing crack with the microstructure of the material and the stress fields. The description and interpretation of fracture markings used to understand failure events are presented in classic textbooks[1,2] and documented by standard organizations.[3–5] Fracture of restorative dental materials is sometimes a result of multiple crack systems from different

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causes, but often is a result of one primary crack system that can be traced back to a single fracture initiation site, or *fracture origin*. Characteristic markings indicative of the crack path are often visible on fracture surfaces. These features can be used to trace back to the failure origin from which the entire fracture process developed. The origin is both a location (a site from which the fracture commenced) and a specific flaw or irregularity at that site. The appearance of these marks will depend on the nature of loading (tension, shear, bending, fatigue, torsion), the presence of stress concentrators and environmental factors, and the microstructure of the material (ie, the reflectivity and roughness of the fractured surface). Glasses, fine-grained ceramics, and some resin composites are fractography-friendly materials, meaning that crack features are recognizable on the fracture surface. In more glassy materials, fracture surface analysis is generally more easily accomplished.[1–3]

The American Society for Testing Materials (ASTM) has developed a standard for fractography and characterization of failure origins in advanced ceramics under the designation of C 1322-96a,[4] and a nomenclature for fracture features has been developed.[1–4] Recognition of these markings is called *descriptive* or *qualitative* fractography and constitutes the first step in any failure analysis.[3] It is used to locate failure origins, determine directions of crack propagation, learn the sequence of crack propagation, and determine interactions between crack fronts and inclusions, grains, etc. *Quantitative* fractography utilizes the measured sizes of fracture surface characteristics to quantitatively determine the stress state at failure based on fracture mechanics relations.[6]

Only a few publications in the dental literature have dealt with fractographic failure analysis of dental ceramics or bisphenol glycidyl methacrylate (bis-GMA) resin.[7–15] These publications focused mainly on determining the origin of the fracture,[6–11] calculating the fracture toughness of the material,[13,14] or correlating toughness and size of crack-arrest lines.[15] One of the reasons for the limited application of fractography is that many dental materials, such as those that are porous, coarse-grained, or multiphase, do not have clear fracture surface markings that are easy to interpret. A description of 3 crack features using qualitative fractography on 3 in vivo failed all-ceramic crowns was recently published.[16] The present paper extends this line of dental fractographic research. The goals of this descriptive study were to use qualitative fractography to: *(1)* recognize characteristic fracture features of mirrors, mist, hackle, wake hackle, twist hackle, velocity hackle, and arrest lines; *(2)* identify the direction of crack propagation; and *(3)* assess design inadequacies of the failed restorations based on the fractographic findings. This research will also extend the previous findings to include fractographic markings on glass fibers embedded in resin composite. Explanations and definitions of the fracture markings and fracture process are given in the Results section.

Materials and Methods

Table 1 summarizes the cases selected. The materials examined were:

1. A fused silica rod (Heraeus Quarzglas)
2. A glass fiber knit (Tec-Knit 6181-08) embedded in resin composite
3. Replicas of in vivo crown veneering porcelain failures of 3 different ceramic systems: *(a)* Cerestore (originally produced by Coors Biomedical) aluminum oxide (Al_2O_3) and alumina-magnesia spinel (70% vol. fraction), injection molded and sintered; *(b)* In-Ceram (Vita Zahnfabrik) slip-cast Al_2O_3 (70% vol. fraction) infiltrated with lanthanum glass; *(c)* feldspath-based porcelain-fused-to-metal (PFM)
4. In vivo recovered fractured ceramic crown (Procera AllCeram, Nobel Biocare), Al_2O_3 (99.9% vol fraction), cold isostatically pressed and sintered

The clinical cases presented were collected as they became available by one clinician (the first author). When original failed parts could not be recovered, in situ replicas were made of the fractured surface of the ceramic crowns using a quadrafunctional hydrophilic siloxane impression material (Aquasil ULV, Dentsply De Trey). The impressions were poured with epoxy resin (Epofix Resin, Struers) and gold coated for scanning electron microscopy (SEM) analysis. The recovered in situ fractured Procera crown and tooth restored with a fiber post and a mesial-occlusal-distal composite core were ultrasonically cleaned for 5 minutes in a 35% ethanol solution prior to sputter gold coating for SEM observations. Magnifications ranged from 10× to 10,000× depending on the size of the characteristic marks investigated.

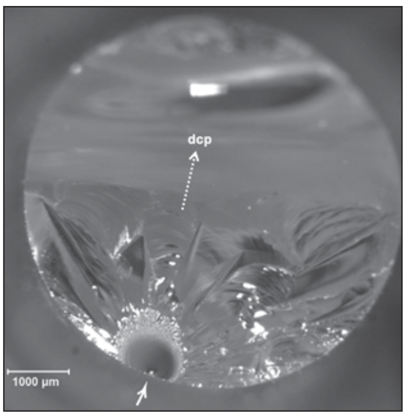
Results

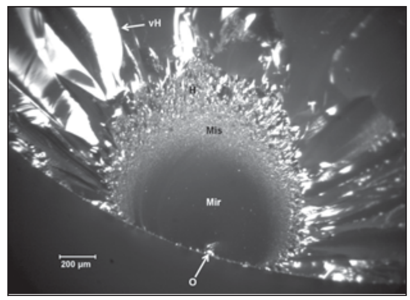
Case 1: Glass Rod (Mirror, Mist, Hackle, Velocity Hackle)

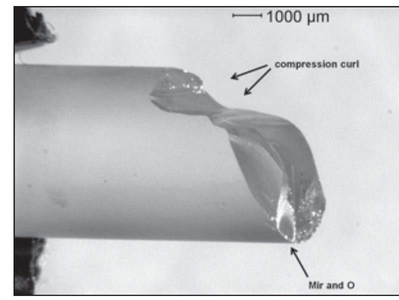
A 6-mm-diameter glass rod, tested in flexure, was used as a reference material for identification of the classic markings known as *mirror, mist,* and *hackle.* Glass is often an ideal material for exhibiting fracture surface patterns, as it is homogeneous and isotropic and has no microstructure interfering with the crack front. Figures 1a and 1b show the fractured surface of the

Table 1 Failures Studied

Case	Material	Composition	Manufacturing process	Original or replica
Case 1 (lab)	Glass rod	Silica	Fused	Original
Case 2 (lab)	Glass fiber knit	Silica	Knitted	Original
Case 3 (clinical)	Procera AllCeram	Alumina	Cold isostatic pressed and sintered	Original
Cases 4 and 6 (clinical)	Cerestore	Alumina-magnesia spinel	Injection molded and sintered	Replica
Case 5 (clinical)	In-Ceram alumina	Alumina	Slip cast	Replica
Case 7 (clinical)	PFM	Feldspath-based veneering	Cast and sintered	Replica







Figs 1a to 1c Classic mirror (Mir), mist (Mis), hackle (H), velocity hackle (vH), or crack branching and origin (O) of a 6-mm-diameter glass rod, broken in flexure (96.2 MPa). The direction of crack propagation (dcp) and origin are indicated by arrows. Fig 1c is a partial side view of a similar specimen, such that both the fracture surface and the side of the specimen are in view. The cantilever curl is readily evident. The origin is a small crack on the surface from grinding.

glass rod, broken in bending, viewed with an optical stereomicroscope (Wild M10), which is an ideal instrument for fractographic analysis because of its good magnification range, good depth of field, long working distance, and ability to project a 3-dimensional view to the observer. Under the application of a critical stress, a crack starts at the origin (O), located at the surface. As the crack propagates, a very smooth and reflective region surrounding the fracture origin is visible, called the *mirror* (Mir). In this region, the crack velocity is too low to cause crack bifurcation and deflection; therefore, the crack front remains relatively planar and the associated fracture surface rather smooth (featureless). As the crack progresses, its velocity increases. When it approaches a maximum (~1,500 m/s after only a short distance traveled), the stored energy is partially dissipated through nucleation of microcracks in the vicinity of the crack tip, creating a rough and less reflective region called *mist* (Mis). This region is rather difficult, often impossible, to discern in polycrystalline materials.

At some point, while the crack propagates, its maximum velocity is reached and enough energy is available to create secondary cracks. The resulting markings are *hackle* (H) and correspond to lines on the crack surface created while the crack is moving dynamically. These lines run parallel to the direction of crack propagation. There are slight differences in the height of portions of the crack front as it radiates outward, and the links and steps between the crack portions are the hackle lines. Depending on the amount of stored elastic energy at the time of failure, the crack front may leave larger daggerlike marks called *velocity hackle.*[3] At that point the crack velocity becomes constant.[1]

Stored elastic energy, or *strain energy,* is directly proportional to the stress in linear elastic materials, eg, most glasses and ceramics. Thus, in situations or loading conditions where the failure stress is low, there is little stored energy, a large mirror region, and little or no velocity hackle or crack branching. Such conditions can occur when the material has large flaws or is under an adverse environment. For example, since silicate glasses break under lower stresses in the presence of water, the associated mirrors are larger.[17] When the low stress and associated low-stored-energy failure are caused by a large flaw, the mirror size is also larger. As a consequence, a rough estimate of the flaw size can be made by noting the mirror size. In glasses, mirrors have been shown to be approximately 10 times the size of the flaws they surround.[18] In 1920, Griffith invoked the first law of thermodynamics to theorize that an increment of crack growth occurs when the change in strain energy is sufficient to overcome the surface energy of a material.[19] This approach applied only to ideally brittle materials that failed from stored elastic energy, although a modification in 1948 by Irwin[20] extended the Griffith energy balance to include deformable materials such as metals. Such energy criteria form the basis of the field of fracture mechanics. Fractographically, ideally brittle materials such as glasses and ceramics, which fail without plastically deforming, are the easiest to analyze because they directly follow the Griffith energy balance.

Hackle and velocity hackle are the most recognizable features on a fractured surface radiating from the mirror region and are thus often used to trace back to the fracture origin. The direction of crack propagation (dcp) runs from bottom to top (dotted arrow) in Fig 1.

Also in Fig 1a, there is a horizontal shadowed ridge at the upper quarter of the fractured rod. This is *compression curl* and indicates there was a flexural component to the failure stress. This feature is shown more clearly in Fig 1c, which is a partial side view of a similar specimen that shows both the fracture surface and the side of the specimen. The cantilever curl (ie, compression curl) is readily evident. The origin is a small crack on the surface from grinding. Compression curl is usually found near the exit side of the crack, and it curves off the plane of initial crack extension that is perpendicular to the tensile stresses on the lower half of the specimen.

In cases where there is a great deal of stored elastic energy (high-stress failures), the crack may bifurcate, trifurcate, or even divide into many pieces. The more available energy there is, the more pieces will be formed at fracture; thus, the stored elastic energy is balanced by the surface energy of the newly formed broken pieces.

Only modest magnifications (10× to 100×) are needed to show the fracture markings and even the origin in the bulk glass rod specimen in Fig 1. The fracture origin in this case was a small surface crack introduced during finish grinding of the outer surface of the rod. The origin can readily be detected, but a clear view of it and its size and morphology often requires higher magnification (100× to 1,000×) and good depth of field at the higher magnifications of an SEM. The fracture markings and origins for the following examples were photographed with an SEM. Normal fractographic analysis usually entails a combination of optical and scanning electron microscopy.

The fracture mirror in the glass rod was a telltale feature that helped us find the exact origin. Fracture mirrors occur in moderate to highly stressed parts, wherein the propagating crack attains high velocities. On the other hand, in many ceramics or weak glasses, the stresses and resulting crack velocities are not sufficient to form a well-defined mirror, or the microstructure is so coarse that the fracture surface is very rough and masks the mirror markings. In these cases, other fractographic features must be observed to trace the fracture back to an origin.

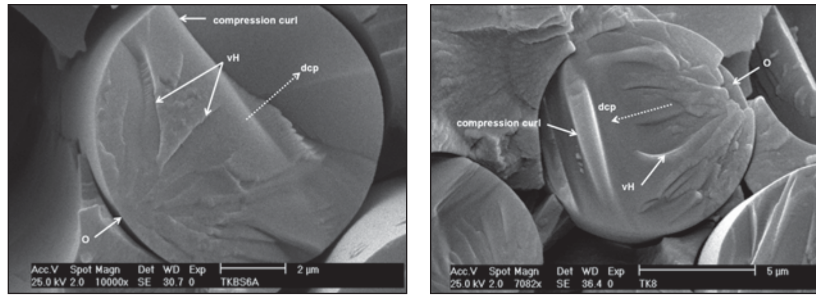
Case 2: Glass Fiber (Velocity Hackle)

Figures 2a and 2b show the fracture surface resulting from a very small glass fiber (~9 μm diameter) knit embedded in resin composite. The SEM is needed to discern the fracture marking in this small fiber. The bulk resin composite specimens had been tested in tension. *Velocity hackle* (vH) are discernible in both figures pointing back to the mirror region and origin (O) area (located on the surface edge). These features attest to high stress in the glass fiber. The direction of crack propagation (dcp) is indicated by the dotted arrow. The end of the fracture process is indicated by compression curl in the fiber, suggesting a flexural component as the crack breaks through the fibers. By tracing back the mirrors and compression curl in the individual fibers, the location of the failure origin of the whole component can be determined.

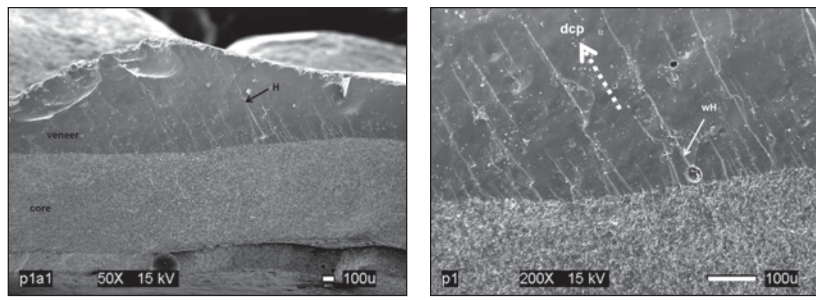
Fractographic features in glass fibers, such as mirrors in the micron range, are not uncommon. Such features have been used, for example, to estimate toughness and the effect of processing parameters in glass fibers used in laser power transmission and optics.[21] The Fig 2 example, however, shows that fractographic features in fibers can also be a useful adjunct to failure analysis in dentistry.

Case 3: Procera AllCeram Crown (Hackle, Wake Hackle)

The images seen in Figs 3a and 3b are from a recovered fractured Procera crown that failed after 1 year of intraoral function. The rough alumina ceramic core (seen at the bottom of the figure) is covered by a glassy veneering porcelain in which many parallel running hackle lines are visible. Hackle is a good indicator of the direction of crack propagation, because it tends to point back toward the crack origin. Such clues are especially helpful when the origin is not visible. In this case, there were additional features that helped determine the direction of crack propagation (dcp). The question in the Fig 3 micrographs is whether the crack was running from the core toward the veneer or from the veneer toward the core. This question can be answered by noting the voids (pores) associated with the hackle (Fig 3b). When an advancing crack front encounters a pore or other discontinuity, the crack proceeds along either side of the void and eventually reforms a continuous crack front on the other side. As the crack advances along the sides of the pore, however, it continues on slightly different planes. This causes a surface irregularity that leaves a trail (wake) emanating from the bubble called *wake hackle.*[1,3,4,16] The localized direction of crack propagation is therefore known and indicated by a dotted arrow in Fig 3b.



Figs 2a and 2b Velocity hackle (vH) pointing back to the origin (O) of a glass fiber embedded in composite resin. General direction of crack propagation (dcp) is indicated by the dotted arrows. Compression curl corresponds to the end of the fracture path.



Figs 3a and 3b Through-thickness fracture of a Procera molar crown after 1 year. Parallel running hackle (H) is clearly visible on the porcelain veneer. The direction of crack propagation (dcp) is given by wake hackle (wH) extending from a discontinuity (a pore in this case) (Fig 3b). In this case, the fracture progressed through the core material first, then ran through the veneer.

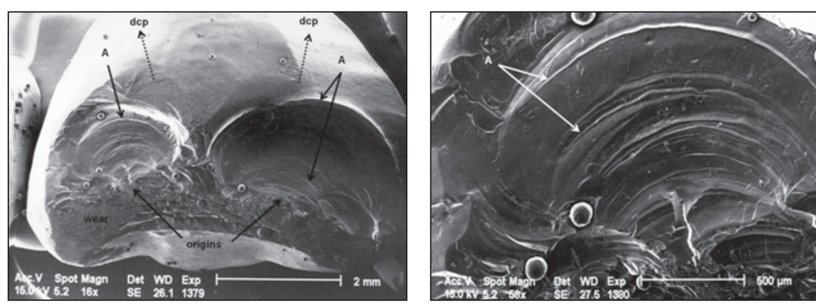


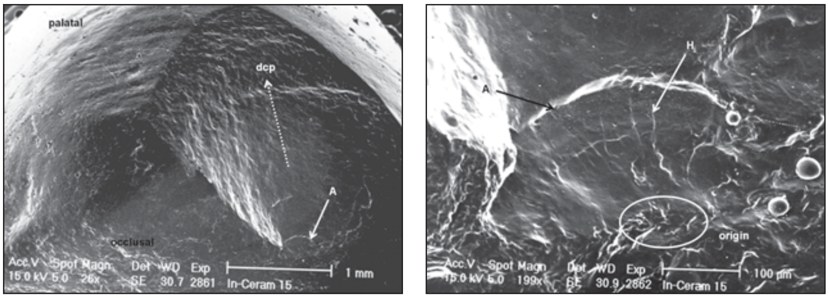
Fig 4a and 4b Replica of a Cerestore lateral incisor failure after 5 years. The veneering porcelain shows 2 parallel running chips starting from the incisal edge. Major wear is visible on the palatal incisal edge. Many arrest lines (A) on the chipped surface indicate the momentary crack halt before resuming again. The origins are located somewhere in the center of the chips, on the concave side of the first arrest lines near the incisal edge, resulting from contact loading. The general direction of crack propagation (dcp) is indicated for each chip.

Case 4: Cerestore Crown (Arrest Lines)

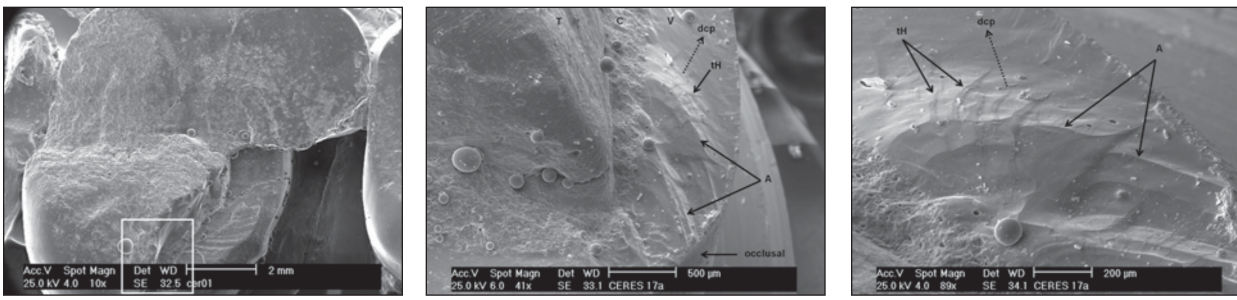
Another characteristic feature indicating the direction of crack propagation is an *arrest line* (also called *rib mark*). This is a well-defined line produced when the crack comes to a halt, before resuming its propagation, often in a slightly different direction. Figure 4 shows a replica of a maxillary lateral incisor Cerestore crown from which the veneering porcelain chipped off after 5 years of intraoral function. A large wear surface over the entire palatal-incisal edge indicates chewing or bruxing activity from friction with the opposing mandibular incisors. The 2 parallel shell-shaped chips likely occurred from contact loading of the mandibular teeth with the abraded incisal porcelain edge of the crown. The 2 crack events left clear semicircular *arrest lines* with similar spacing. Arrest lines give the shape of the crack front and are useful in locating the failure origin that would normally be on the concave side of an arrest line. The exact location of the failure origin(s) (indicated by arrows) corresponds to a contact area at the intersection of the wear region and the incisal edge at the center of the semicircular arrest lines. The direction of crack propagation (dcp) is indicated by the dotted arrow, which runs from the incisal edge toward the cervical region.

Case 5: In-Ceram Crown (Arrest Line, Hackle)

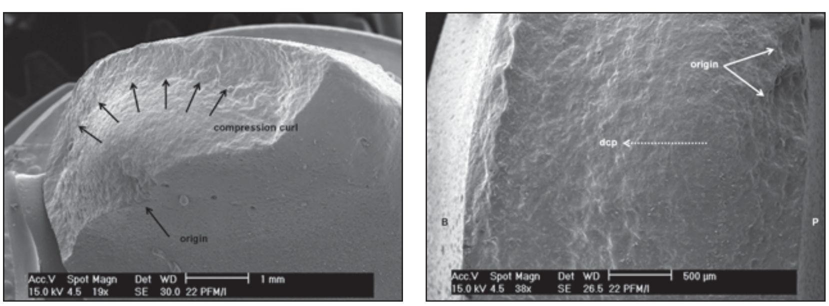
Another fracture surface replica of a veneering porcelain is shown in Fig 5. The fracture of this maxillary In-Ceram premolar occurred after 9 months of intraoral function. The occlusal-palatal view shows contact wear (rough surface) from the antagonist tooth. A clearly defined semicircular arrest line (A) is visible above the wear contact region (Fig 5b). Some hackle (H) is recognizable on the concave side of the arrest line pointing back to the origin (O), a contact area located within the circled surface at the intersection of the rough (worn) and smooth (fractured) porcelain. This crown failed from contact loading. The general direction of crack propagation (dcp) is indicated by the dotted arrow.



Figs 5a and 5b Replica of an In-Ceram premolar veneering fracture. The porcelain chip is located on the palatal cusp. An arrest line (A) is visible on the occlusal side of the chip. Hackle (H) can be seen on the concave side of the arrest line point back to the origin resulting from a contact load (circle) and worn porcelain surface. The general direction of crack propagation (dcp) is known thanks to the arrest line and hackle.



Figs 6a to 6c Replica of a failed Cerestore upper molar after 18 years showing a heavily worn occlusal surface (Fig 6a). The 41× magnified views (Figs 6b and 6c) of the occlusal palatal angle of the crown (rectangle in Fig 6a) show several arrest lines (steps) (A). The direction of crack propagation (dcp) is indicated by the concavity of the arrest lines. Twist hackle (tH) is shown in Figs 6b and 6c.



Figs 7a and 7b Replica of an incisal angle fracture of the veneering porcelain of a PFM crown. Arrows indicate a zone called compression curl—a curved lip indicating the end of the fracture process. The origin (O) is therefore located on the opposite side of the compression curl. The higher magnification (in b) shows 2 semicircular indents (impact by mandibular incisors) located on the palatal side and corresponding to the origin of the failure event.

Case 6: Cerestore Crown (Arrest Lines, Twist Hackle)

Figure 6 shows a replica of a fractured Cerestore molar crown after 18 years of intraoral function. At the occlusal palatal crown angle (Figs 6b and 6c), on the porcelain veneer, arrest lines (A) are recognized, indicating that the crack propagated in steps. This suggests successive loads were applied. Also visible is *twist hackle,* which occurs when the principal tension axis undergoes a lateral rotation (twist). The hackle that separates portions of the crack surface briefly twists in a direction normal to the new tension axis before resuming in parallel but non-coplanar crack propagation. In this case, the fracture started from the occlusal contact area.

Case 7: PFM Failure (Compression Curl, Impact Damage)

Figure 7 was obtained from a replica of a maxillary incisal porcelain veneer fracture of a PFM crown that failed after 3 months of intraoral function. At a low magnification (Fig 7a), compression curl on the buccal side of the crown is evident (arrows). As previously mentioned, compression curl (also known as cantilever curl) is indicative of flexural stress. A crack starts and grows perpendicular to the tensile surface of a specimen or component loaded in bending. As the crack grows, it approaches the compression side of the specimen, slows, and veers away (maintaining a perpendicular relationship to the tensile stress field), leaving a curved lip just before total fracture. Compression curl is common in failures of rectangular bars used for bend strength tests, where it is often used to quickly determine the side opposite the one that contains the initiating flaw.[16] Based on the presence of the compression curl, the end of the fracture is located on the buccal side of the crown, therefore the palatal (opposite) side was searched for a starting flaw (origin). By rotating the specimen and tilting the SEM, the fracture origin area could be located in the form of 2 adjacent damage sites, resulting from contact impact of the mandibular lower incisors. Excessive occlusal contacts generated by the mandibular incisors during mastication were responsible for the early failure of the structure.

Discussion

Crown Design Deficiencies and Occlusion

The fracture surface analyses of a chipped veneering porcelain of a Cerestore incisor crown (case 4, Fig 4) and an In-Ceram premolar crown (case 5, Fig 5) showed, for both cases, evidence of surface wear near the starting area of the crack. An excess of wear (bruxing function of the patient) on the Cerestore crown remained clinically unnoticed and resulted in thinning of the incisal edge, which in turn became more prone to surface chip fractures. Early detection of such bruxing activity could have prevented the failure, with an overnight acrylic resin mouthguard provided for the patient to protect the ceramic crowns. Premature contact on the In-Ceram premolar crown resulted in contact damage from the opposing dentition, and either the porcelain or the patient's opposing dentition should have been adjusted to prevent this. A similar conclusion is drawn from the porcelain failure of the PFM crown (case 7, Fig 7). Because this failure occurred in a very short time (3 months), no wear was visible, but the 2 impact indents seen under SEM are evidence for an excess of occlusal (palatal) porcelain thickness. The crown was supported by an implant; thus, no periodontal ligament was present to absorb the impact shock. Again, a careful initial occlusal adjustment would have prevented this early failure.

Importance of Qualitative Fractography

The topography of a fractured surface contains classic crack patterns characteristic of the material and associated stress state. Recognition of these markings is important for understanding part, if not all, of the failure history. Qualitative fracture surface failure analysis relies upon recovery of the failed parts without additional damage.

As stated in the standard ASTM C1322,[4] fractography is best performed on in situ recovered specimens and should include careful examination of both mating halves of the primary fractured surface for determination of the fracture origin and size. Nevertheless, most clinical failures occur unexpectedly and in a sudden manner. The emergency patient rarely has recovered the broken piece and appears at the dental office with functional and esthetic needs that must be addressed immediately. Retrieval of the still in situ remaining failed part without damaging the fractured surface is a nearly impossible task, as these crowns are strongly cemented. Therefore, in all cases, a quick replica—in the form of a 5-minute elastomeric impression of the fractured crown—should be performed before trying to recover or destroy the evidence. Such replicas were used for the analysis of cases 4 to 7. The fine reproduction of the fractured surface allowed efficient recognition of classic features, providing information on the direction of the crack propagation and sometimes indicating the fracture origin. Limitations of replicas include air bubbles when pouring the epoxy resin, inability to determine subsurface features via transmission or transillumination, inability to use color as an indication of material changes or detection of foreign inclusions, and some blurring of very small features. Depending on the nature of the material and its microstructure, the crack features will be easily or barely discernible. Hence, the reference glass illustrated in case 1 was presented as an ideal example of the classic crack features left during crack initiation and propagation. The difficulty of detecting such features can increase with the crystalline content of the material, grain size and shape, amount of transgranular and intergranular fracture, and relative size of the fractographic features. Thus, core materials with a high crystalline content and large grain size—such as many aluminas (Cerestore, In-Ceram, Procera)—can be challenging in terms of discerning crack surface features. In the case of Procera, only the veneering porcelain exhibited hackle lines. These differences in material and reflectivity complicate the task of fractographic analysis and point out the importance of analyzing in full scale the recovered parts.

Conclusion

Identification of crack initiation sites and fracture progression from fractographic analysis is of key importance in providing scientific evidence of the possible defective nature of the restoration (legal aspects) or whether the component was overloaded in stress-bearing areas. Such data are strongly needed to gain knowledge of clinically relevant failure stresses, improve the final product quality, and set some realistic limits on the clinical use of available materials in posterior regions.

Universities therefore should develop internal expertise for fractographic analysis of failed specimens, helping the scientific community as well as clinicians to understand failure. Clinicians, on the other hand, can greatly contribute to this effort by providing fractured parts, replicas, images, and failure history of the component. This paper is an educational attempt by the authors in that direction, describing the fractographic analysis process in a variety of clinically relevant examples.

Acknowledgments

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Literature Abstract

Strengths of composite bonded to base metal alloy using dentin bonding systems

The purpose of this experiment was to compare the shear bond strengths of 7 bonding systems achieved when bonding a hybrid composite to a base metal alloy surface that was polished and air abraded. Circular buttons were fabricated using a Ni-Cr-Be alloy and were imbedded in autopolymerizing acrylic resin. The specimens were arbitrarily divided into 8 groups of 10 specimens each and treated with one of the adhesive systems used in the study (All-Bond 2, Optibond FL, Panavia 21, Perma Quick, Obtibond Solo, Prime & Bond 2.1, 3M Single Bond). Herculite hybrid composite (Kerr) was loaded into a No. 5 gelatin capsule. Composite was then light polymerized from 3 angles for 30 seconds for each angle. A mechanical testing system was used to fracture the composite from the metal and an analysis of variance (ANOVA) was calculated using the collected data. The following conclusions were drawn: *(1)* All-Bond 2 achieved the highest shear bond strength of all the bonding systems tested, but was not significantly higher than 3M Single Bond of Optibond FL; *(2)* there was no significant difference in shear bond strength between the single component and the multicomponent system group; *(3)* the dentin adhesive systems exhibited higher shear bond strengths than the resin cement system; and *(4)* the use of primer did not increase the shear bond strength for Panavia 21.

Knight JS, Sneed WD, Wilson MC. *J Prosthet Dent* 2000;84:149–153. **Reference**: 15. **Reprints**: Dr James S. Knight, Department of General Dentistry, MUSC College of Dental Medicine, 173 Ashley Ave, PO Box 250507, Charleston, SC 29425. Fax: 843-792-2847. E-mail: knightjs@musc.edu—*Khaldoun Alajlouni, UNMC College of Dentistry, Lincoln, NE*