Fractographic Analysis of All Ceramic Restorations

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Abstract

Why did it break? Where is the origin? Did it break from an unexpected cause? Was there a problem with the material or was the crown or bridge simply overloaded? Was it misused? Was the crown fabricated properly? Was there a fitting problem? These are common practical questions and the fractographer can often give answers. Analysis of ceramic restorations can be difficult, but fractographic analysis is a cumulative learning experience. Our skill level is improving rapidly as we learn to recognize and interpret telltale fracture patterns. Our progress and several representative clinical case studies are presented.

Introduction

All-ceramic dental crowns are increasingly being used as alternatives to gold or porcelain fused-to-metal restorations. A variety of ceramic materials have been used, including feldspathic or luecite porcelains, glass ceramics, aluminas and zirconias. The fracture resistance and durability of the new ceramic crowns are a primary concern. Fractures occur in spite of the best efforts of researchers, manufacturers, technicians, and dentists.

The curse of brittle materials is that they are prone to catastrophic fracture. Brittle fracture takes place with little or no plastic deformation. Nature has partially compensated for this shortcoming by furnishing fracture patterns and fracture surface markings that provide a wealth of interpretable information. Unfortunately, many dental ceramics are very difficult to interpret due to their microstructures. Many dental ceramics have coarse-grained or porous microstructures and fracture at low stress. Classic fractographic markings are often masked by the roughness of the fracture surface. A rough rule of thumb is that the greater the stress and energy of fracture, the more fracture surface markings are created. Service stresses that cause fracture may be lower than

the stresses reached in laboratory test specimens such as bend bar or disk strength coupons. Bend bars and disks are not too difficult to interpret and are a good starting point for an aspiring fractographer. Crown fractures are different since the loadings may be unknown and stress states are transient and uneven. Evidence is incomplete or contradictory. Key fragments are often missing, either due to loss in the mouth or damage during crown extraction. Crowns often accumulate damage from multiple events at different sites creating complex fracture networks.

The fractographer quickly learns that classic fracture markings[1,2] such as fracture mirrors (that unequivocally draw attention to an origin) are rarely present in crowns or bridges. The resourceful fractographer must look for other telltale features to make an interpretation. Ceramic fractures occur from many causes and after a chain of events. One event may create a flaw, but then a second or even third event may be necessary to cause fracture.

Fractographic analysis is not merely looking at fracture surfaces, but is the integration of knowledge from a variety of sources to solve the puzzle of how and why a fracture occurred. Most good fractographers, whether they are experts in metals, ceramics, polymers, or composites, realize they must keep an open mind when interpreting fractures.[2,3,4] The skill of a fractographer is in knowing where to look and how to look. When the fractographer applies his or her pattern recognition skills and recognizes key telltale signs, then he or she can make a definitive interpretation. Good fractographers are cautious and recognize the limitations of their experience base. They do not overreach or extrapolate. They should be alert to unusual or new fractographic markings or failure modes with which they are not familiar and should be ready to search the literature, consult colleagues, or try to create comparable markings in the laboratory. No fractographer is born with a built-in data base of fractographic patterns in the brain, so step-by-step accumulation of experience is necessary. Our team[5-10] and others[11-15] are accumulating that experience for dental ceramics. This presentation outlines some of our progress.

A new Guide to Fractography of Ceramics and Glasses[2] has been prepared by NIST and will be published soon. It covers the fundamentals of fractographic analyses of brittle materials and has many illustrations. The Guide is intended to help general users learn how to do fractographic analysis of brittle materials. Some dental ceramic cases are included in the Guide.

A crown fracture analysis entails careful examination of the available fragments or replicas of the crown with special emphasis on the fracture surfaces. Although there are many possible fracture markings in glasses and ceramics, a few key types are commonly found in dental ceramics. These can be interpreted to ascertain the local direction of crack propagation. The crack propagation is backtracked to its source, the origin of fracture. Examinations are with the unaided eye, a stereoptical microscope at magnifications typically from 8 X up to 100 X (but sometimes to 400 X), and with the scanning electron microscope (SEM) from typically 10 X to 2000 X. Sometimes an analysis can be done entirely with one or the other microscope, but the microscopes are best used as complementary tools as will be shown below. The most common fracture surface markings that aided our analyses were wake hackle from pores in the veneer, shear hackle when a crack went around a corner, and cantilever curls from bending and final rupture of a crown. Details of these markings and how they form have been documented previously.[1,2,5] Other types of markings[1,2] such as gull wings, arrest lines, witness marks, blunt contact cracks, edge chips, contamination, and staining of the fracture surfaces are helpful. Our emphasis in this paper is to show how these markings can be used to discover a fracture origin and to identify the general mode and cause of in-vivo fracture of all ceramic crowns.

Case A

Figures 1 and 2 show a Cerestore[a,b] alumina-magnesia spinel fractured molar crown that was documented by J. Quinn et al. in Ref. 5. This was an upper molar crown that failed after 17 years. It is likely a left mandibular first molar. The uncoated crown was initially examined with an optical microscope. A gold coating was then applied to the fracture surfaces to prepare the specimen for the scanning electron microscope, but also to enhance a second optical examination. The coating cuts down on internal reflections and light scatter making the fracture surface easier to discern. In the optical photographs the gold coating has made the veneer look dark and the core material lighter. The fractographic markings for this and the following cases are explained in the captions to the figures.

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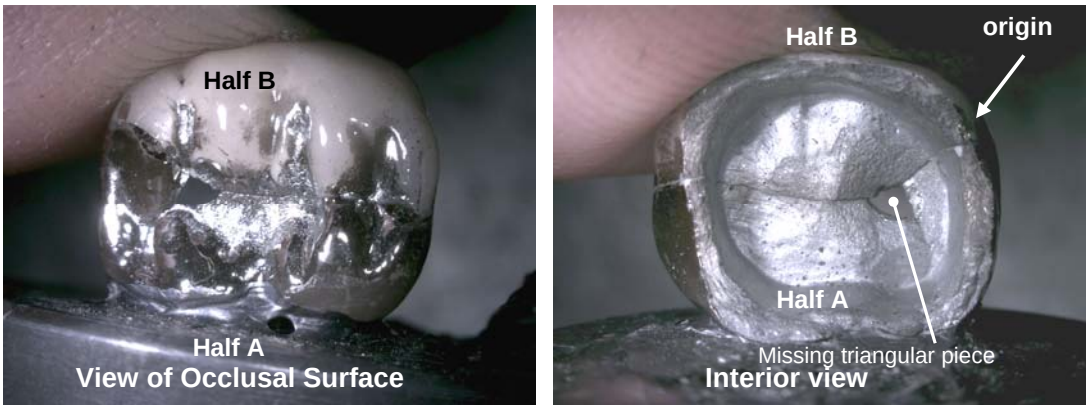
[a] Originally developed by Coors Biomedical, Lakewood, Co.. Available later from Ceramco Inc., East Windsor, NJ.

[b] Identification of commercial products is included to adequately specify the experimental procedure and does not imply endorsement by the authors, institutions or organizations supporting this work. Likewise, the inclusion of a specific material for failure analysis does not suggest that the material has an increased probability of failure.

These markings allowed us to determine that the origin was located at the margin of the crown and the vertical split nature of the fracture suggests that hoop stresses around the bottom of the crown caused the breakage. A specific material flaw or source crack could not be identified at the origin. At the present time we are unable to discern or recognize such a flaw in this particular material, but with more experience we expect to be able to acquire this skill. By the time the crack propagated over to the opposite side, the two halves hinged apart in bending thereby creating the telltale cantilever curl.

Figure 1 Case A. Fractured Cerestore alumina-spinel molar crown with an origin on the margin. (a) is a top occlusal surface view showing the two cleaved halves held together. Such handling is permissible with brittle materials, provided that it is done carefully.[2] Half A is fully-gold coated and half B is partially-gold coated. (b) shows a view of the interior looking up into the crown. The missing triangular piece was caused by secondary breakage. The origin was on the margin, at the bottom of the crown. (c) shows an optical photo of the fracture surface of half B with arrows showing the direction of local crack propagation (dcp). The dark outer regions are the gold-coated glassy veneer. The lighter gray inner portions are the gold-coated core ceramic material. Close-ups of three identified regions are shown in the next Figure.

(a) (b)



(c)

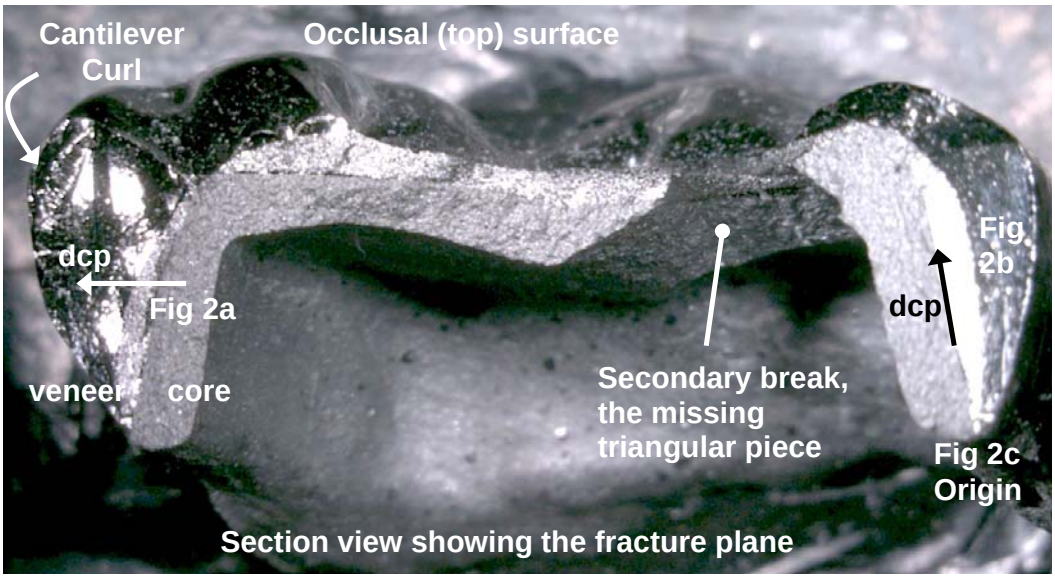
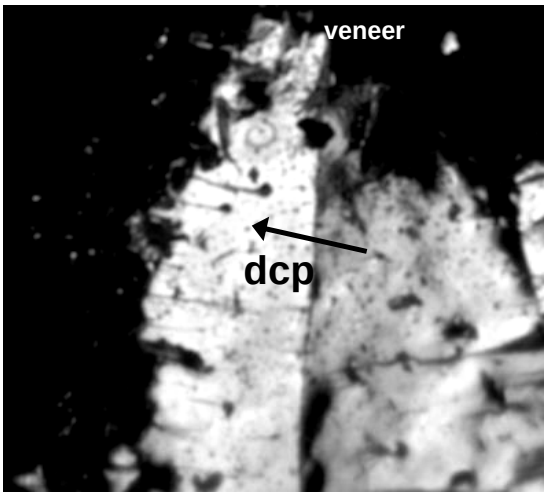


Figure 2 Case A continued. Fractured Cerestore alumina-spinel molar crown. (a) shows "wake hackle" from tiny bubbles in the veneer glass. Wake hackle is a step in the fracture surface created by a crack passing by an obstacle. The step points in the direction of local crack propagation. This location is on the left of view Figure 1c and indicates the direction of crack propagation (dcp) was as shown by the arrow. (b) shows wake hackle and faint "gull wings" from bubbles in the veneer on the right side of the crown. At this location the crack was running in the direction of the arrow from the margin (bottom) of the crown to the top. Careful scrutiny of the adjacent core ceramic material showed that it also had wake hackle generated by pores in the ceramic, and pointed in the same direction. (c) is an optical image at the margin with working notes of the origin area. A distinct flaw is not recognizable in either the veneer or the core.

(a)



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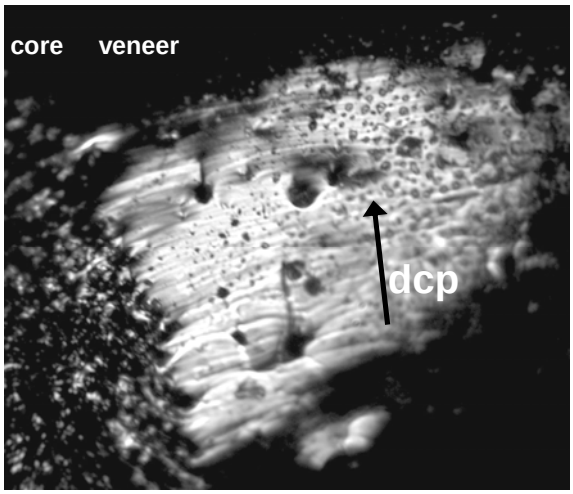
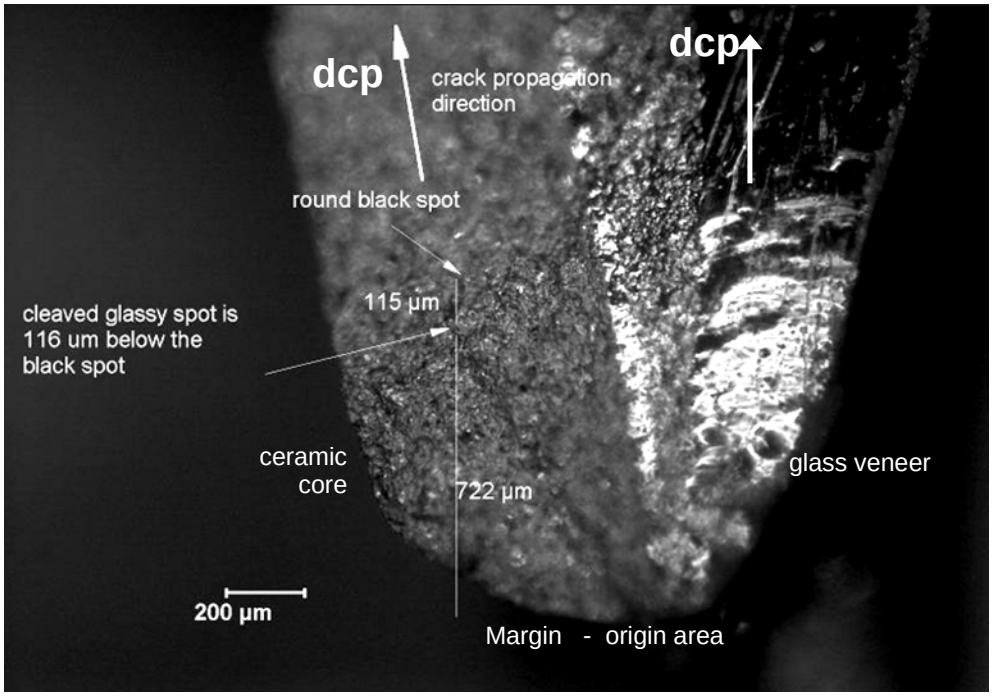


(c)



Case B

Figure 3 shows a similar case, also from Ref. 5, but for a Procera®AllCeram 99.9% purity alumina.[c] This crown broke after one to two years of use. It also split vertically, probably in response to hoop stress. The fractographic markings again lead to a margin origin site. A specific single origin is also not evident in this case. Nevertheless we observed that the origin site is on the inside of the crown coincident with the end of the cement bond to the core material. This site undoubtedly is susceptible to stress concentrations.

Case C

The third crown, also a Procera®AllCeram alumina, is shown in Figures 4 and 5. This is an upper premolar crown that fractured after four years of intra-oral function. The patient remembered biting on something hard. One half of the broken crown was available for examination. In hindsight, it may have been advantageous to have taken a replica of the matching half that was destroyed during extraction, but we were fortunate that the retrieved piece had all the relevant information for a analysis. Unlike the two previous cases, we were able to make a full analysis in this instance and find the exact origin flaw. This crown failure was analyzed in about one hour solely on the basis of an examination with a stereo optical microscope. Figures 4 a-f are optical images of the crown from that examination. As such, some of the details were "washed out" and do not reproduce well, but they are shown to demonstrate what an optical microscope examination can reveal. Keep in mind that the fractographer has a much better and clearer view when looking through the microscope. Subsequent scanning electron microscope examination produced sharper images shown in Figure 5.

Fracture in this crown occurred in multiple steps. One event created an initial chip flaw on the margin. Subsequent exposure and use caused a second crack from this chip, but on a different plane which ran up and split the crown. Hoop stresses generated by normal oral function caused the crack propagation.

Shear hackle around the inside corners of the core, a cantilever curl, and wake hackle again led back to the margin-initiated fracture origin. The origin was a well-defined edge chip on the

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[c] Nobel Biocare, Stockholm, Sweden.

Figure 3 Case B. Procera alumina molar crown. The crown split vertically into two halves. (a) and (b) show the fracture surface after gold coating. The veneer glass is dark and the core ceramic is a lighter shade. The arrows show the local direction of crack propagation as indicated by shear hackle around the inside corner, the cantilever curl, and from wake hackle markings in the veneer. (c) and (d) are examples of wake hackle from pores in the veneer. (e) and (f) show optical and SEM images of the margin, respectively. The origin is in the core ceramic at the stress concentration site at the end of the cement bond. (dcp = direction of crack propagation)

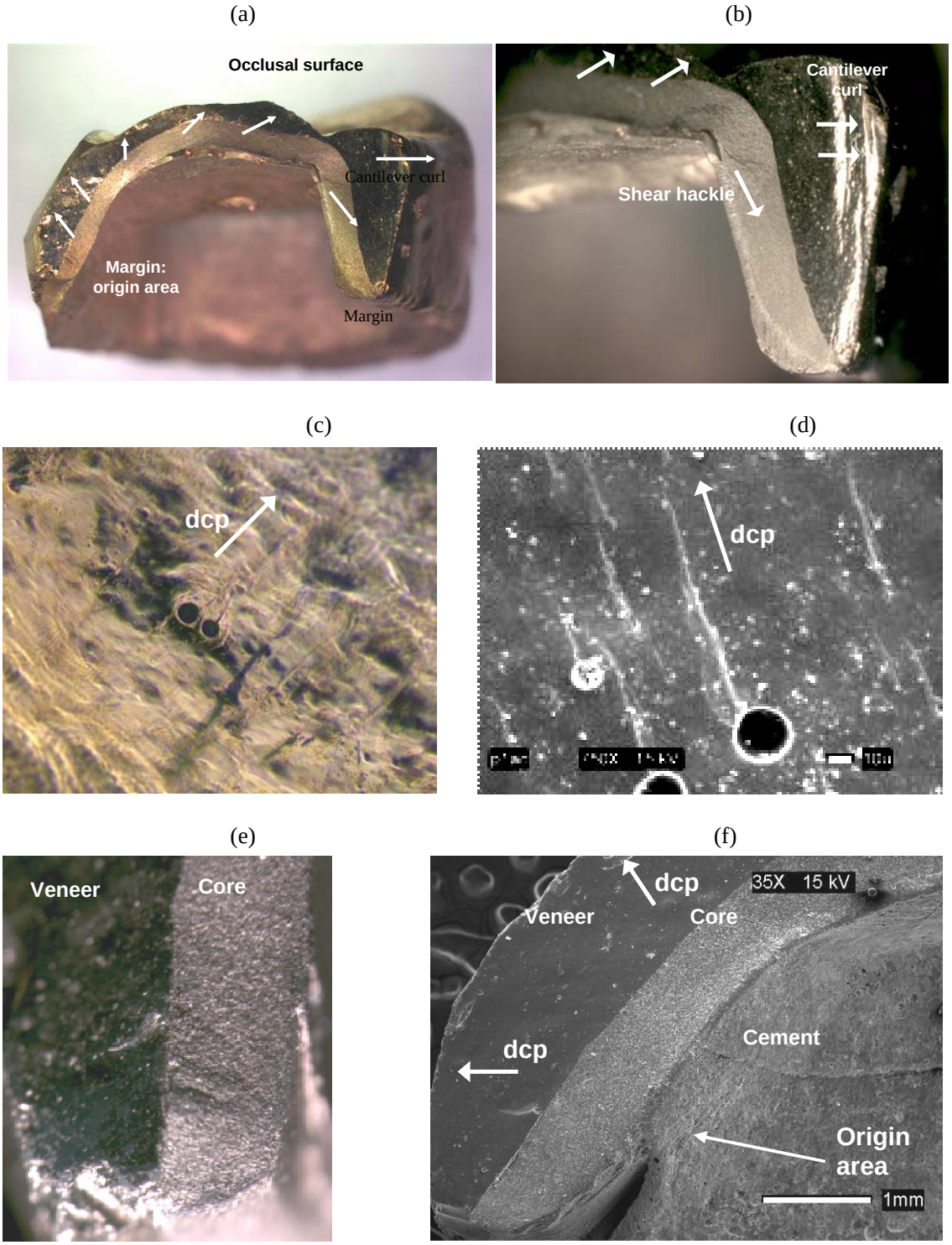


Figure 4 Case C. Procera alumina molar crown that broke from a margin chip. These are optical images without any coatings. (a) is a clinical view with the origin marked. (b) is one half of the fractured crown. (c) shows a fanlike array of shear hackle (between the two arrows which show the propagation direction) in both the veneer and core emanating from the top inside corner. (d) is from near the margin on the left side and shows tiny wake hackle from veneer pores. The crack ran from bottom to top. (e) and (f) show the origin was an edge chip from a force applied on the bottom of the margin aimed upwards. (dcp = direction of crack propagation)

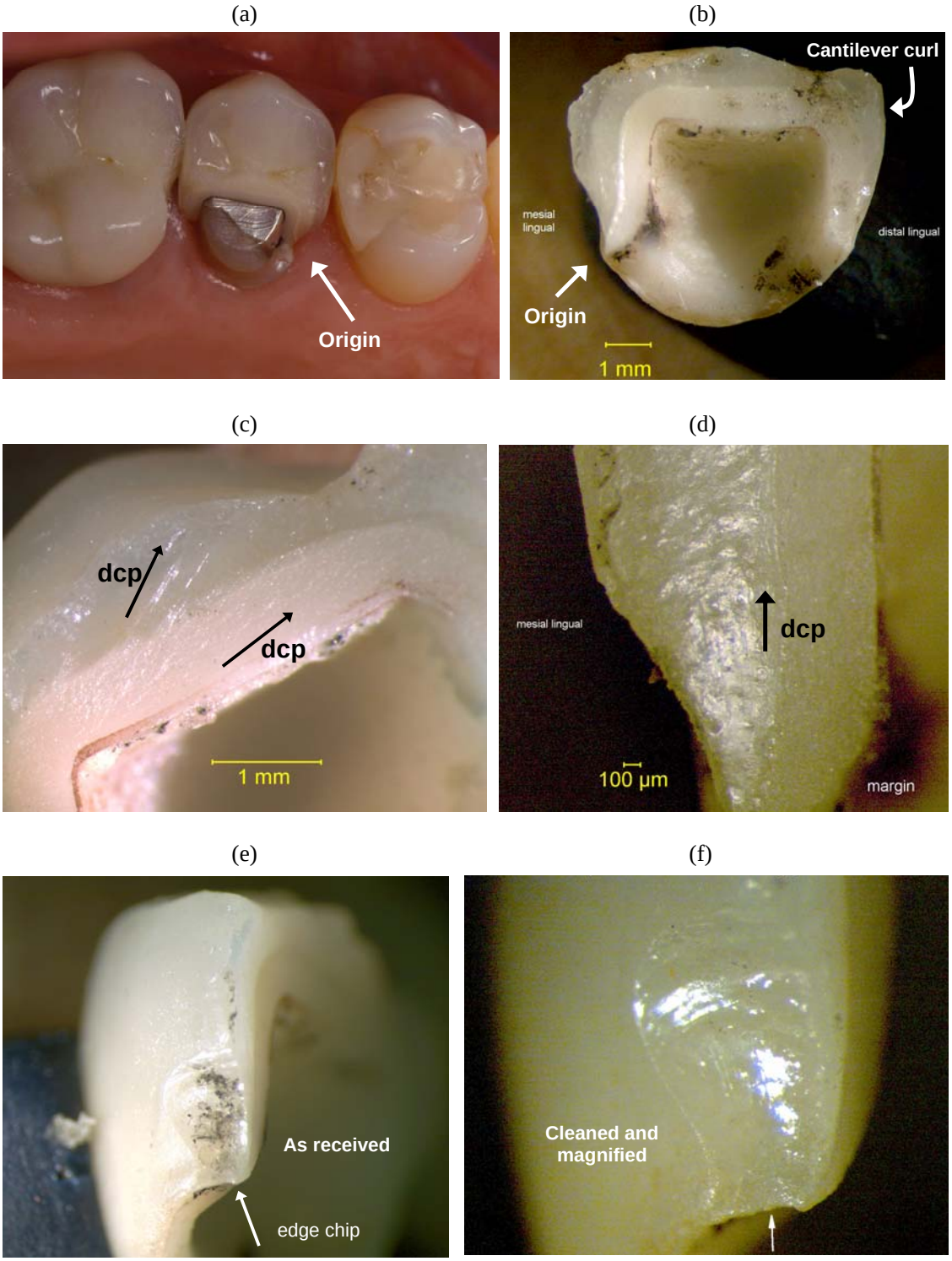
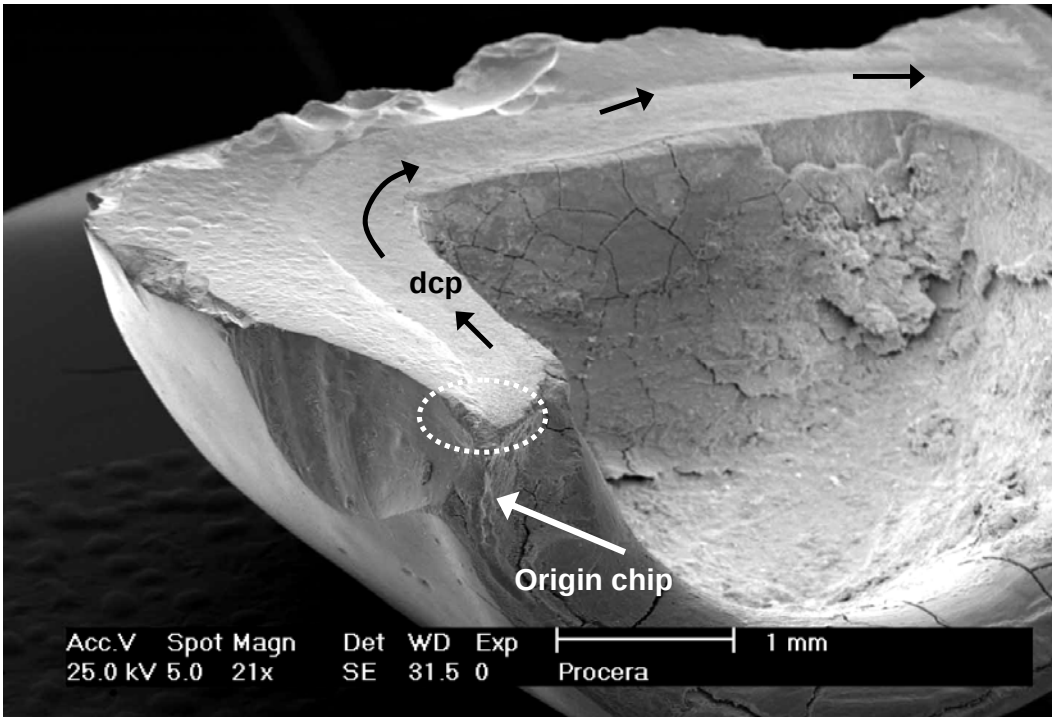
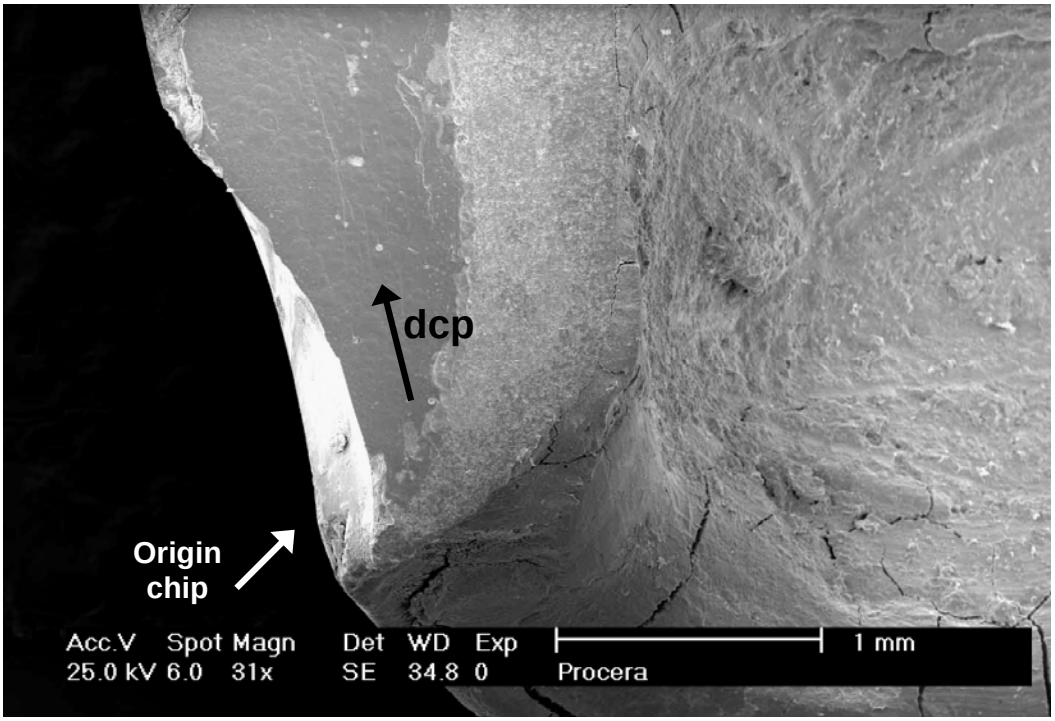


Figure 5 Case C continued. SEM views of the fractured crown. There are two fractures. The first was the margin chip (white arrows). The second fracture that split the crown started at the bottom at the margin in the circled area in (a) from part of the prior margin chip. The second crack ran as shown by the black arrows.

(a)



(b)



veneer. The edge chip was discolored suggesting that it had been present for quite some time. Gum tissue had grown into the space vacated by the chip, further indicating that the chip fragment had been gone for some time. The direction of the edge chip was interesting since it appeared to have been from a force directed upwards on the margin on the underside of the crown. The chip was probably created during fabrication or installation. The chip fragment separated from the crown and could have been docile if the patient was lucky. Unfortunately for the patient, localized cracking damage near the initiation site of the chip grew into a second large crack on a different plane that eventually propagated up into the crown body and finally split it. Ionomer cement and discoloration were observed on the fracture surface in a region near the occlusal surface suggesting that this portion had been fractured for some time prior to the ultimate separation of the piece. Some small fractures in the form of edge chips reached down from the occlusal surface, but these were all incidental, secondary, and occurred after the crown split. The edge chips showed no indication of having affected the path of the primary crack. (Such secondary cracking often can be dismissed by simply observing whether they match features on the opposing fractured half. If they do not match, then it is safe to assume the cracking was secondary.) So the patient's "final bite on something hard" did not cause the most of the damage. It simply led to the final separation step.

Case D

The fourth case shown in Figures 6 – 10 is an Empress 2 lithium silicate glass ceramic crown.[d] This crown was presented in Reference 5, but new analysis has refined our interpretation. This anterior (#7) incisor crown had been in service only 4 months when it split into two pieces. The fracture plane was again vertical and perpendicular to the dental arch. No information was furnished on how the fracture event occurred or how the crown was fabricated or installed. Tool grinding marks on the lingual surface veneer suggested that there were some fitting problems. The two halves fitted closely together. A few small chips were missing, probably from secondary fracture, and were inconsequential to the analysis.

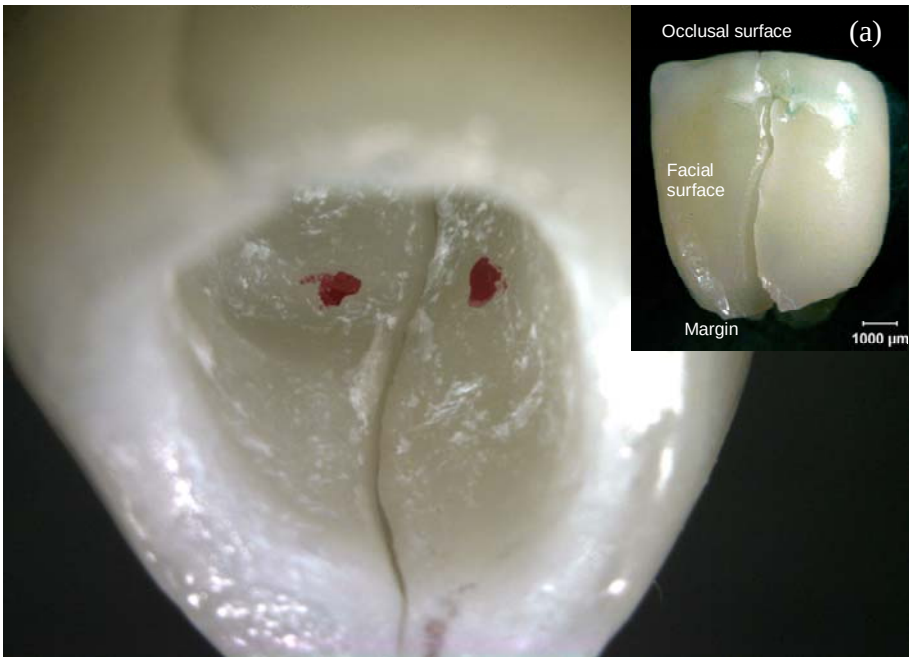
The lingual surface had some usage surface damage and also an unusually thick veneer. There were several shallow depressions (≈ 1 mm^2 square area) as well as numerous conchoidal chip

[d] Ivoclar, Schaan, Liechtenstein.

fractures, small pits and gouges at mid crown height. The shallow depressions had tool marks indicating they were from adjustments to the lingual surface, presumably by the dentist once the crown had been cemented in place and opposing tooth contact checked. This adjustment was only partially successful in relieving contact from the opposing tooth as evidenced by the numerous small pits, chips, and gouges. This location was near the fracture origin region.

Figure 6 Case D. Fractured Empress II glass ceramic incisor cemented crown. The insert (a) shows a facial view of the cleaved crown. (b) and (c) show views looking up into the interior with the two halves together. The origin is located between the two marked dots on the inside surface. Residual cement has been cleared away.

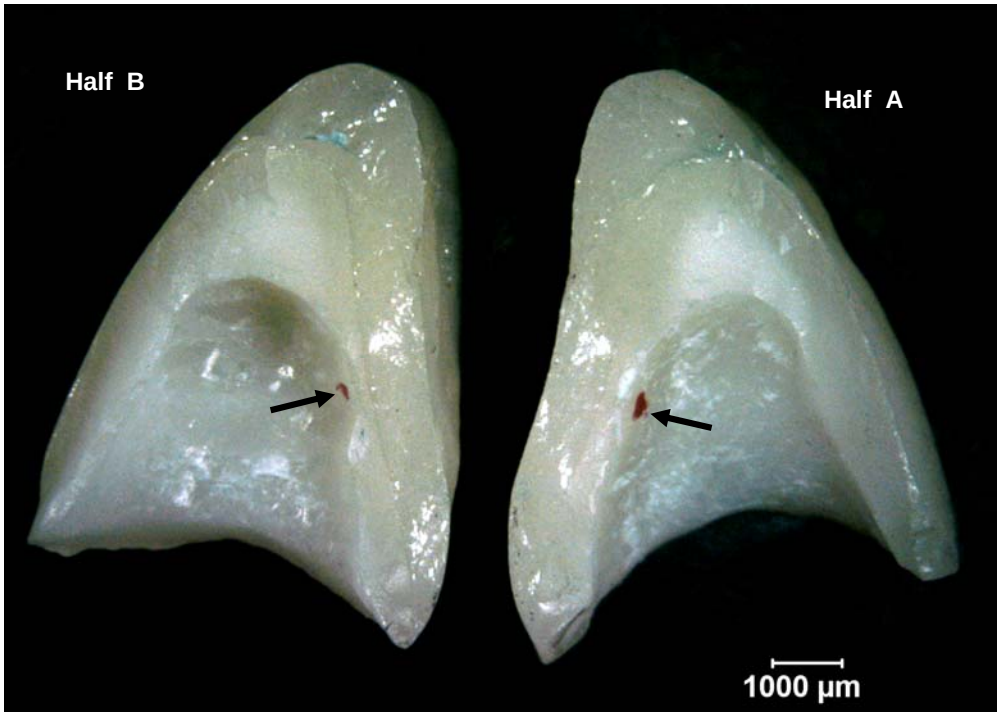
(b)



(c)

Figure 7 Case D continued. (a) and (b) show the fracture surfaces of the two halves. (a) shows an optical photo of the uncoated halves B and A, and (b) shows gold-coated surfaces. The glass veneer coating reflects more. It is evident the veneer thickness is very uneven and out of normal guidelines. It is very thick on the lingual side and very thin on the facial side. The arrows mark the origin site located on the *inside* of the crown at the thinnest part of the core ceramic material.

(a)



(b)

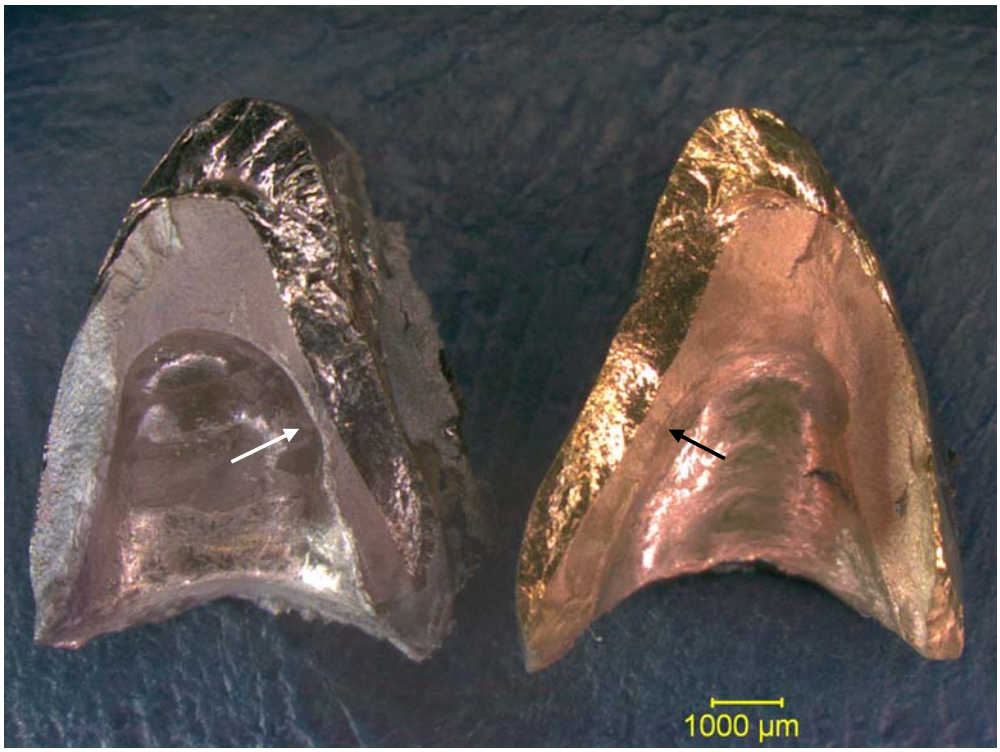
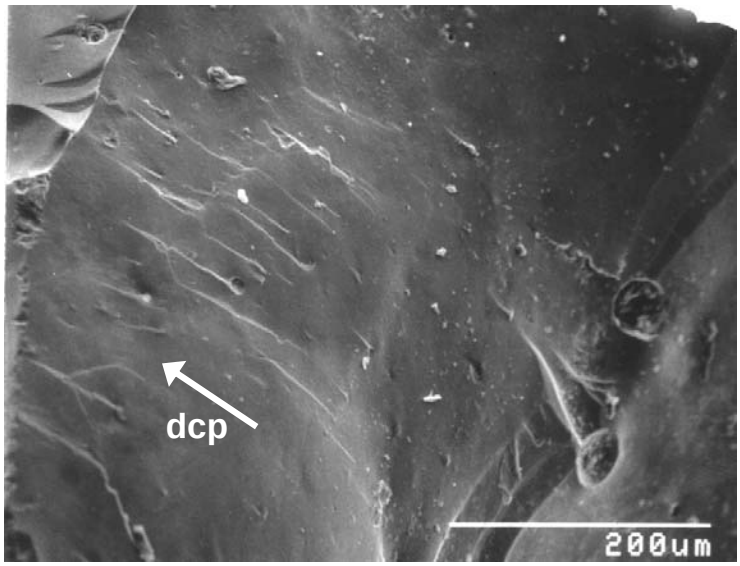


Figure 8 Case D continued. (a) shows an SEM image wake hackle in the glassy veneer from a region near the occlusal surface of the A half. The wake hackle shows that the crack was running in the direction of the arrow in this region. All the wake hackle in the entire crown showed fracture was from the inside to the outside. (b) shows the origin site is a cone crack on the inside surface (arrow). The following photos show this site in more detail.

(a)



(b)

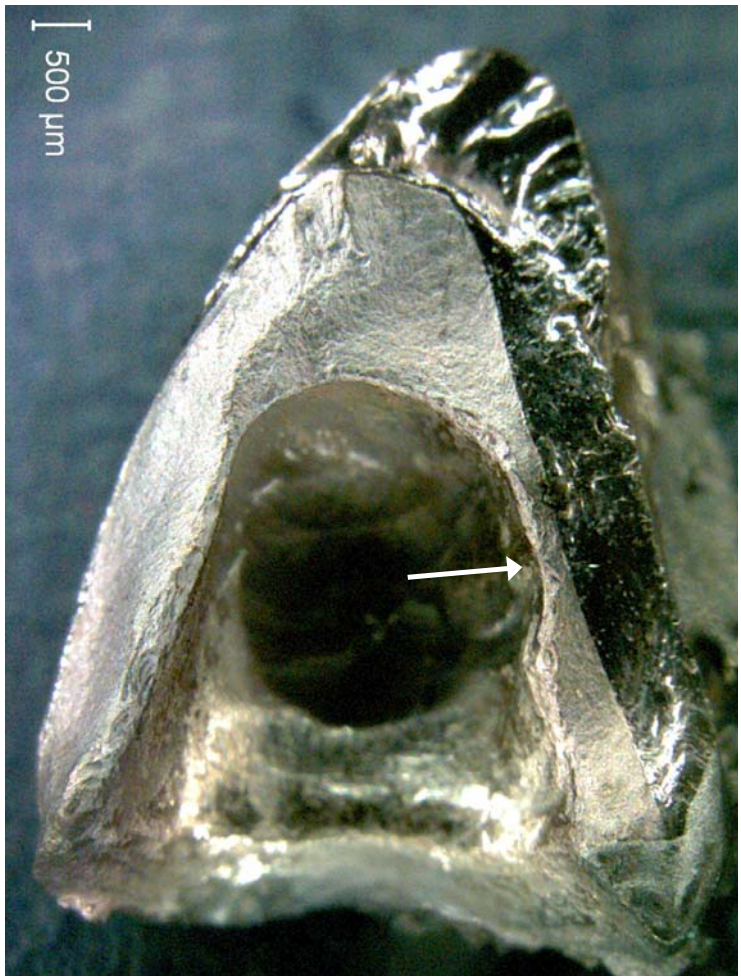
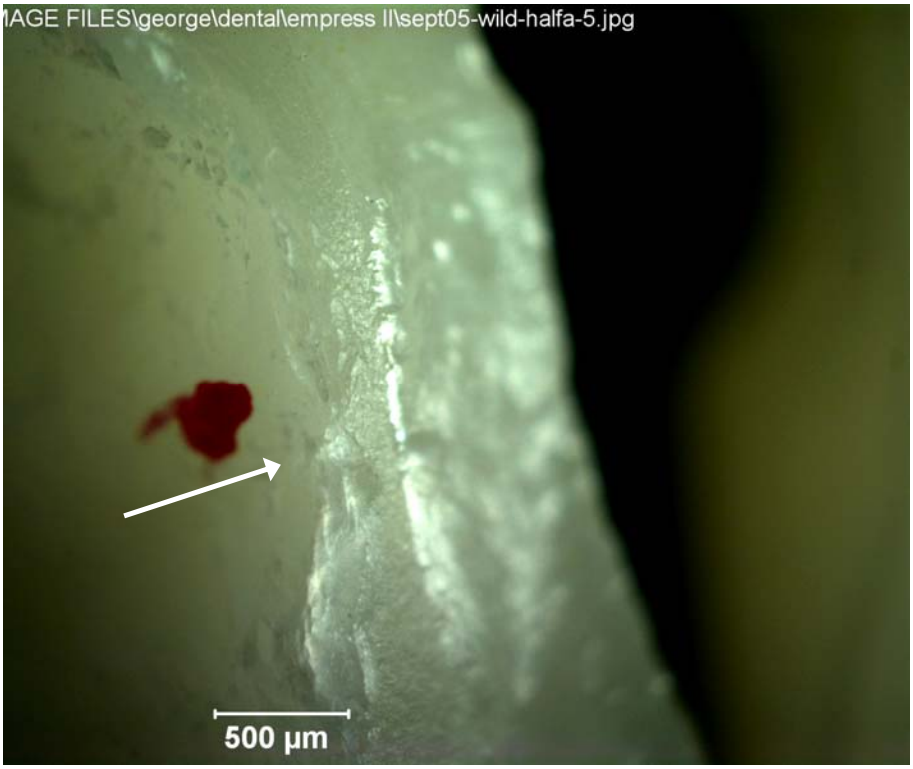


Figure 9 Case D continued. (a) and (b) are optical images of the origin which originated from a contact on the inside of the crown at the thinnest point of the core.

(a)



(b)

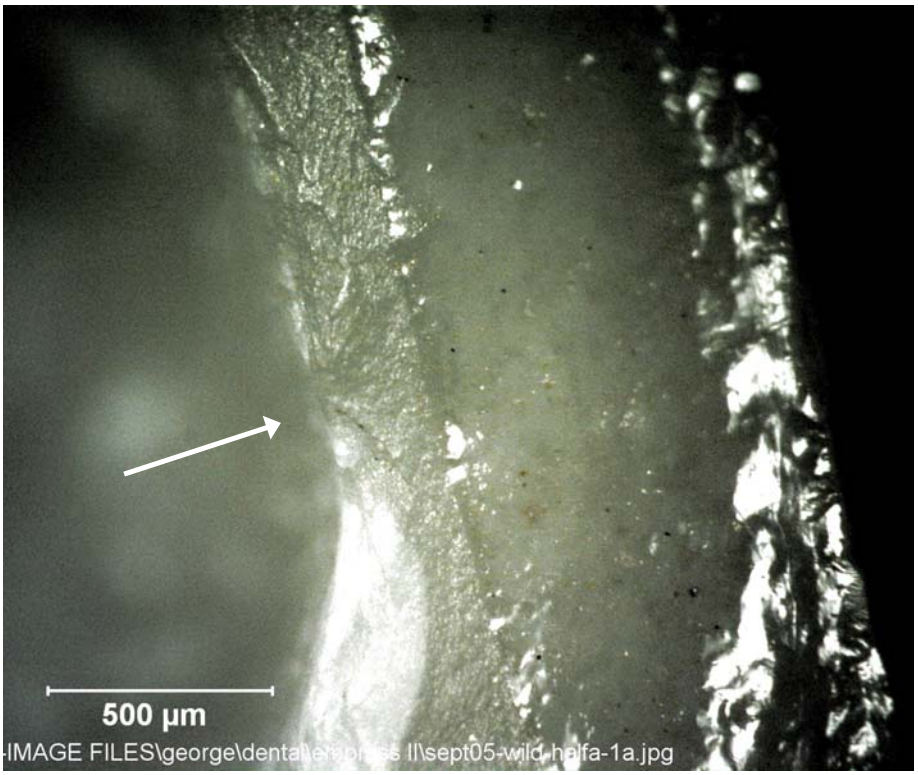
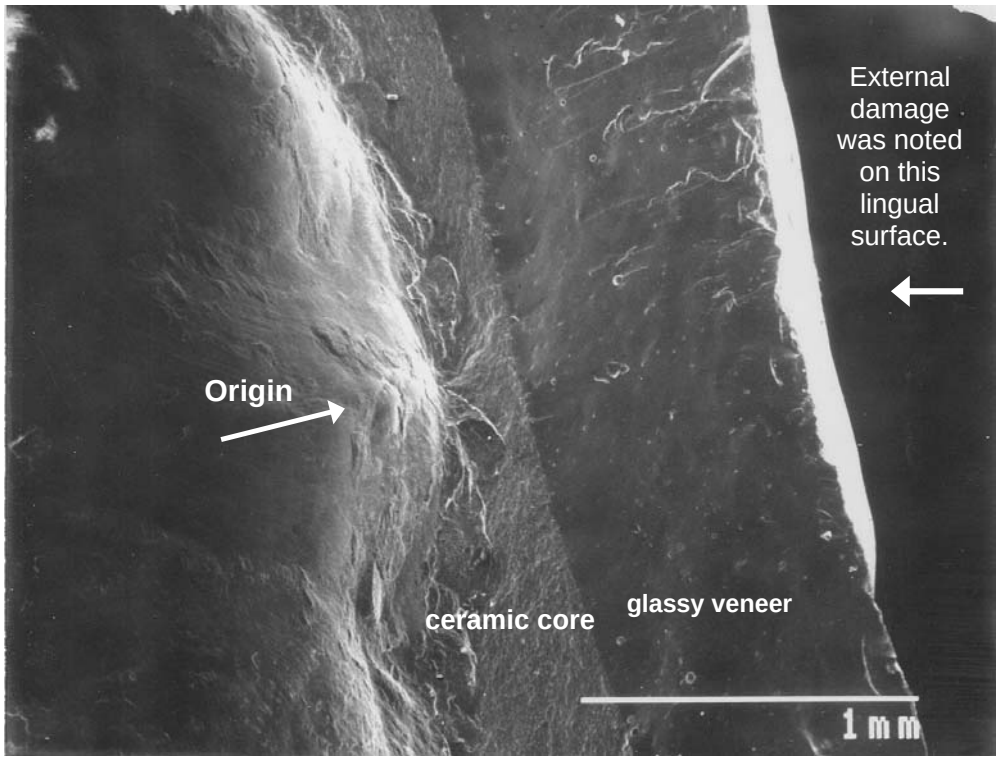
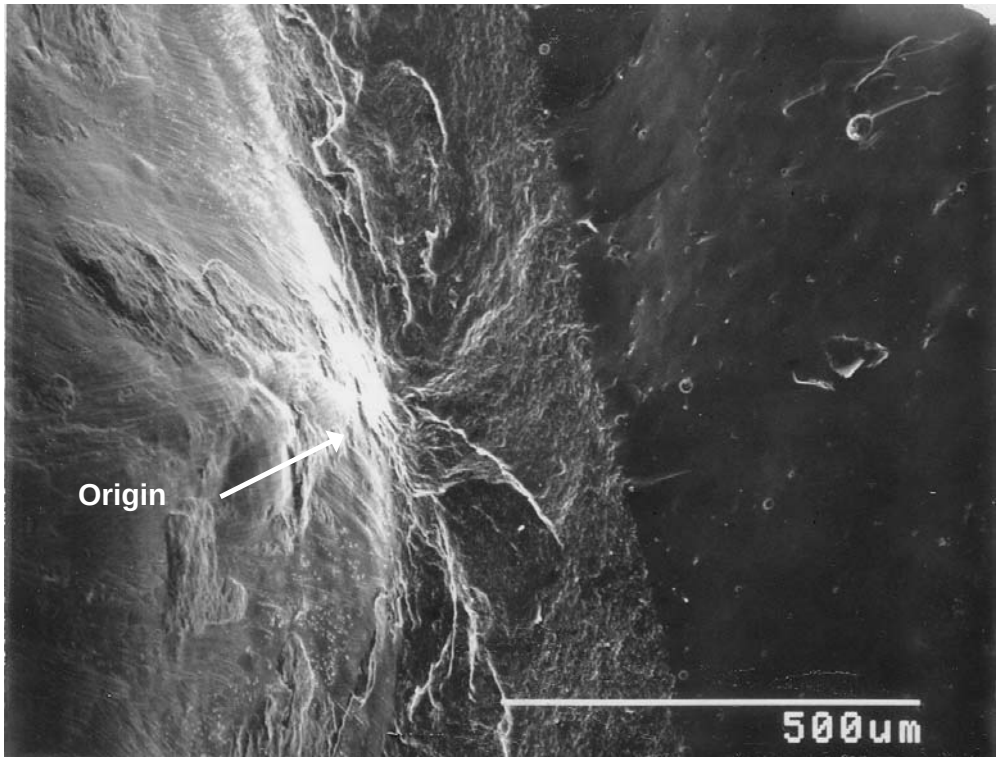


Figure 10 Case D continued. (a) and (b) are SEM images of the origin (arrows). Notice all the wake hackle in the veneer aiming away from the interior. The crack ran from the inside to the outside. The inside surface is uneven and there are mold or tool marks in the vicinity. This region is directly opposite a region of extensive localized contact damage on the exterior lingual veneer surface on the right (not visible in this view).

(a)



(b)



The facial surface was in good condition and had little damage or evidence of abuse. It had an unusually thin veneer that had a few secondary edge-spall chips and one small harmless Hertzian cone crack that did not penetrate into the core material. The edge-spall chips were noted on one fragment but not on the other, indicating that they were secondary fractures that occurred after the crown had broken.

There was negligible damage on the occlusal (top) surface. Tool grinding marks and/or casting impression marks were detected on the inside of the crown.

The application of green tinting dye for an optical examination and a subsequent SEM examination brought out a number of telltale brittle material fracture features. Fractographic markings in the glass ceramic core material were difficult to detect, but subtle hackle markings were similar to features observed on bend strength test specimens of the same material. Extensive wake hackle was detected from bubbles in portions of the glassy veneer as shown in Figure 8a. Seven or eight crack arrest lines were also detected.

This was a difficult case. Initial examinations had only limited success, but repeated careful scrutiny of the fragments using different examination techniques (optical as-received, optical green dye-coated, optical gold coated, and SEM) was successful. Maps of crack propagation direction were constructed, primarily through observations of the wake hackle markings in the veneer. These all led back to the origin. Fracture initiated in the core material (where it was very thin) from an *internal surface* Hertzian cone crack. This location was in the same vicinity where outer lingual surface veneer damage was also detected. Fracture then radiated upwards and downwards in response to hoop stresses. This again was a multiple event failure. One event caused the blunt contact crack. Subsequent repeated loading led to the formation of a splitting crack that oriented itself in response to hoop stresses. This main crack propagated in stages as evidenced by numerous arrest lines in the veneer.

This internal contact damage origin initially had been dismissed as secondary chipping damage, created during extraction or handling. Only after repeated examination was it realized that <u>both halves</u> showed matching damage features characteristic of blunt contact damage at the exact same location on the cementatious surface of the crown. This surface was uneven and had raised hills, ridges and depressions.

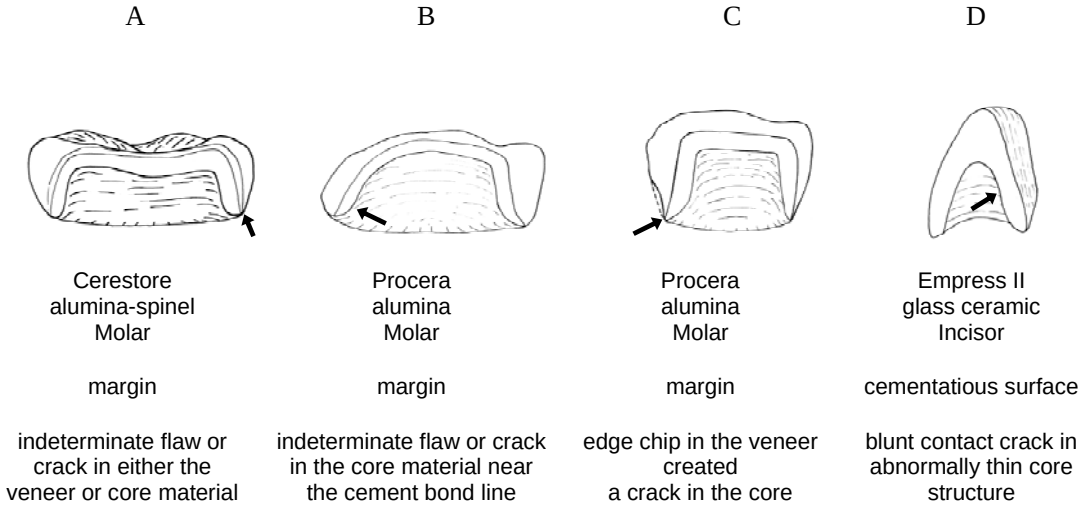
The crown was carefully examined for evidence of residual stresses at the interface of the core and veneer. Such evidence might be crack redirection where the crack approached or encountered the interface. Over most of the crown, there was no such evidence as shown in Figure 10. One incidental region was noted where the crack did change direction at the boundary.

In summary, the Empress II crown had uneven veneer and core wall thicknesses. Fracture initiated from contact damage on the *inside* of the crown, possibly due to a fabrication handling error, or possibly due to an uneven fit. Opposing tooth contact in the same vicinity on the crown exterior surface (as evidenced by shallow pit and chip damage) may have created the initial stresses in the origin area. Surface grinding adjustments and veneer damage in the same area suggested a fitting problem. The final splitting crack was driven by normal usage stresses.

Discussion

These four crowns cases are part of a growing body of fractographic analyses of crown failures. All four split vertically, perpendicular to the dental arch, from hoop stresses. Several crowns showed evidence of multiple events leading to failure. One event created a crack or flaw. Subsequent exposure and stresses led to crack propagation and fracture often on a different plane. Figure 11 shows the summary findings. Specific gross material flaw origins were not be detected in any

Figure 11 Summary findings for the four cases.



of the four crowns. It is important to note that other fracture modes exist. We have observed veneer edge chipping and occlusal surface cracking in other crowns not discussed in this paper. Nevertheless, crown splitting appears to be a common fracture mode. In three of the cases, fracture initiated from the margin region, a vulnerable area due to the thinness of the restorations. Handling or installation damage can easily occur at this location. They can in a sense be considered the "weak link" in a structure. Once any sort of crack initiates in the margin, the crown may be doomed. Ordinary or paranormal usage creates hoop stresses that are a potent driving force for crack propagation. It is also likely that misalignments or misfits of the crown exacerbate stresses at points on the margin periphery. The principal author has seen other non dental ceramic structures where thin webs act as such weak links and preferred sites for crack formation.

The fourth case (Empress 2 incisor) had a very unusual blunt contact crack origin starting on the inside surface of the crown. This was a classic case of where the fractographer had to keep an open mind. Contact cracks are often postulated to be sources of fracture, but to the best of our knowledge, this is the first recorded instance of an internally-generated contact crack origin. This site had a very thin core thickness and was probably prepared improperly. Localized damage on the exterior lingual surface was observed directly opposite this thin core layer initiation site.

Conclusions

Fractographic analysis of dental crowns is very challenging, but promises to be very rewarding. Fractographic analysis is a cumulative learning process. Crown-by-crown, prosthesis-by-prosthesis we are accumulating an experience base of the tell tale signs of various fracture modes for in vivo fractured crowns. Gross material flaws have not been detected to date. Crown design, fabrication, and installation, and the chewing habits of the patient are the primary factors contributing to fracture. Margins are particularly susceptible regions for crack initiation in as much as they are very thin. Veneers are susceptible to contact crack and edge chip damage.

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