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FRACTOGRAPHY OF DENTAL RESTORATIONS

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Abstract. The dental community is using a variety of ceramic restorative materials such as porcelains (leucite or alumina based), glass-ceramics (leucite, mica, lithium disilicates), alumina-glass infiltrated, and CAD-CAM ceramics including pure alumina and zirconia (3Y-TZP) core materials. Polycrystalline ceramics such as alumina and zirconia serve as substructure materials (i.e., framework or core) upon which glassy ceramics are veneered for an improved appearance. Under masticatory loads, sudden fracture of the full-thickness restoration or of the veneering ceramic (chips) may occur.

Stereomicroscope and scanning electron microscope analyses were used to perform qualitative (descriptive) fractography on clinically failed dental ceramic restorations. The most common features visible on the fracture surfaces of the glassy veneering ceramic of recovered broken parts were hackle, wake hackle, twist hackle, arrest lines, and compression curls. The observed features are indicators of the local direction of crack propagation and were used to trace the crack's progression back to its initial starting zone (the origin).

This paper presents the applicability of fractographic failure analyses for understanding fracture processes in brittle dental restorative materials and it draws conclusions as to possible design or processing inadequacies in failed restorations.

Introduction

The dental community has benefited from advances in ceramics to offer a variety of ceramic materials [1-5] for dental restorations using the application of high-technology processes such as hot-pressing, slip-casting, and fabrication of glass-ceramics. The currently available ceramic materials for CAD-CAM (computer aided design / computer aided manufacturing) in dentistry are broad, ranging from feldspathic porcelains (alumino-silicates), leucite, mica or lithium disilicate glass-ceramics, to densely sintered core materials such as alumina or yttria stabilized zirconia. The higher strength, higher toughness ceramics such as alumina and zirconia, thanks to their fully dense crystalline microstructure, serve as core materials upon which glassy ceramics are veneered to achieve the needed enamel looking like aesthetics. These glassy veneering ceramics have little to no crystalline structure and are therefore weak in their mechanical properties with average strength values around 100 MPa and a fracture toughness close to 1 MPa \sqrt{m} .

When using all-ceramic restorations in posterior teeth where high masticatory loads are generated, sudden fractures of the bulk restoration (i.e., through the core) or of the veneering ceramic (chips) may be expected. In a thorough review [6] based on 15 clinical research studies of 5 years, there was insufficient information to connect failures associated with ceramic fractures to the mechanical properties of the ceramic materials mainly due to the fact that no systematic failure analysis was performed on the broken parts. As all fractures in ceramics are initiated at a critical flaw, fracture surface analyses can provide a clear indication of the most probable cause of fracture based on identification of the failure origin and the path of crack propagation. In bilayered ceramic

restorations (i.e., high strength ceramic core covered by a glassy veneer ceramic), the failure origin may occur at a variety of locations such as 1) within the veneering ceramic (chips), 2) the interface core-veneer, 3) the restoration's margins, 4) the tensile stressed surfaces of the core material, or 5) at the connectors in a multi-unit bridge. The types of flaws involved in the failure event may originate from critical processing flaws, including blank pressing flaws, sintering cracks, machining flaws, or from final manual grinding flaws from adjustments with burrs done by the dental laboratory and/or by the dentist. Another source of flaws may come from surface damage resulting from chewing combined with chemical erosion in the oral environment.

The use of fractography for analyses of clinically failed dental restorations was brought to the dental community as early as 1989 but was slow in catching scientific attention with only five publications in the following twelve years [7-11]. Since 2005, however, descriptive and quantitative fractography have been systematically used for analyzing clinical failures of dental restorations by some groups of researchers affiliated with dental establishments around the world [12-20].

From the publications that have specifically listed all fractographic features visible on clinically failed ceramic restorations [12,14,16,17,19] it appears that the most common crack features are hackle, wake hackle, twist hackle, arrest lines and compression curl. With the increased use of all-ceramic restorations as restorative materials, premature failures (< 5 years of intra-oral function) have been reported [20-26]. Mapping the fracture path from recovered parts thanks to the identification of fracture features, and possibly locating the origin, helps one to understand the reasons for early failure and will provide useful information as to processing problems, design errors, and clinical preventive measures for increasing the longevity of these restorations.

The scope of this paper is two fold: first, to use qualitative fractography following the NIST recommended practice guide [27] for understanding clinical fractures of ceramic restorations, and second, based on the fractographic findings, to suggest some laboratory and clinical measures to limit such failures.

Materials and Methods

Table 1 summarizes the seven cases used for fractographic analysis. A total of five veneer chips (four of which are replicas from fractured surfaces) and two bulk core ceramic fractures were analyzed using mainly the scanning electron microscope (SEM). A search for key fractographic features such as hackle, wake hackle, twist hackle, arrest lines, compression curl and surface wear was performed in order to map the crack path and help trace fracture back to an origin.

All the veneer chips occurred during mastication according to the patient's information with the exception of case #4, which was noticed during a recall session by the dentist. The through-the-

Table 1 Description of the clinical failure cases used for fractographic analysis

Failure type	Case ID ^a	location	specimen	Time to failure
Veneer chip	#1 Procera Al	molar	replica	4 years
Veneer chip	#2 PFM molar	molar	retrieved part	1 year
Veneer chip	#3 PFM incisor	Lateral incisor	replica	2 months
Veneer chip	#4 Cerestore	Lateral incisor	replica	5 years
Veneer chip	#5 InCeram Zr	Premolar	replica	2 months
Alumina core	#6 Procera Al	Premolar	retrieved part	Try-in
Zirconia core	#7 Cercon bridge	Lateral incisor	retrieved part	24 hours

PFM = porcelain-fused-to-metal

alumina-core fracture of a Procera®AllCeram (Nobel Biocare, Sweden)^a in case #6 occurred during a try-in session in which the patient was asked to “gently” bite for the final occlusal height adjustment. Case #7 is a 6-unit Cercon® zirconia core bridge (DeguDent, Hanau, Germany) which was cemented with a temporary cement and fractured overnight from biting (pressing) forces. The SEM images for case #7 were documented by Dr. Ulrich Lohbauer from the University of Erlangen, Germany.

To secure information of veneer chip fractures, the replica method [17] was used. It consists of taking an intra-oral impression of the in-situ remaining fractured part by injecting an elastomeric low viscosity silicone material. The impression (which is a negative of the fractured surface) is filled with a cold mounting epoxy resin (Epofix Resin, Struers, Denmark) which becomes a positive replica of the fractured surface which is then gold-sputtered for SEM analysis.

Results and Fractographic Descriptions

1) Veneering ceramic chip fractures

Case #1 (Fig.1): Procera®AllCeram (Nobel Biocare, Sweden) upper left molar crown with a veneer fracture after 4 years of intra-oral use. The replica shows evidence of important occlusal wear related to grinding habits (Fig.1b). The black arrows point to the origin, an area of high contact loading, located on the mesial-occlusal-palatal cusp. Arrest lines and hackle were clearly discernable on this replica (Fig. 1c,d). At higher magnifications (1000 X) wake hackle confirmed the general direction of crack propagation from the chewing surface downwards towards the gingiva.

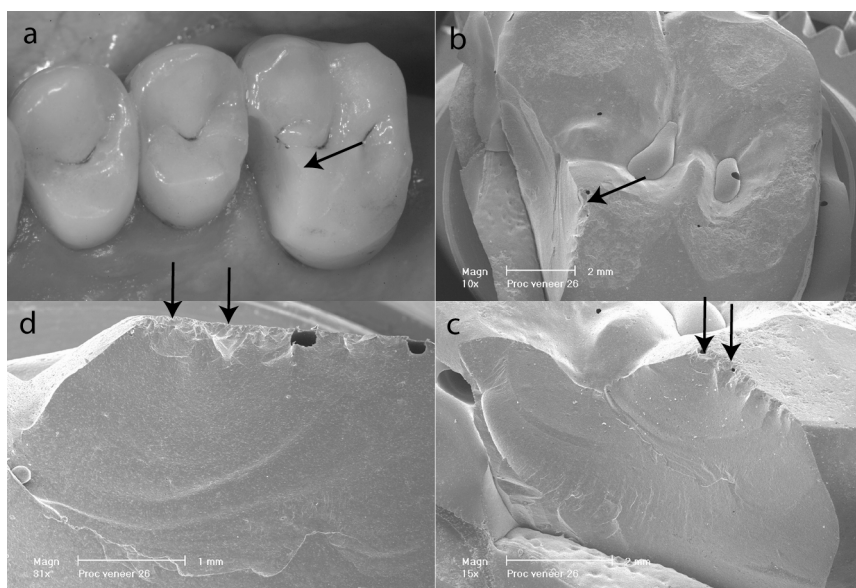


Figure 1. Procera®AllCeram crown molar crown chip failure after four years (a). (b) shows a SEM view from a replica of the occlusal chewing side and the chipped surface. Important ceramic wear facets are visible on the occlusal surface at the level of the cusps. The fractured surface is represented in c,d, showing arrest lines and hackle. The black arrows point to the origin, located on the occlusal mastication surface.

^a Certain commercial materials or equipment are identified in this paper to specify adequately the experimental procedure. Such identification does not imply endorsement by the National Institute of Standards and Technology nor does it imply that these materials or equipment are necessarily the best for the purpose.

Case 2 (Fig. 2): Chipping after one year of the feldspathic porcelain of a porcelain-fused-to-metal crown cemented over a dental implant (Fig. 2a). The SEM image was taken directly on the recovered crown. A compression curl is visible in form of a shoulder on the outer contour of the broken surface (Fig. 2b). The crack origin (black arrow) is located on the occlusal (i.e. chewing) surface next to a contact wear area as seen at higher magnifications in Figs. 2c,d.

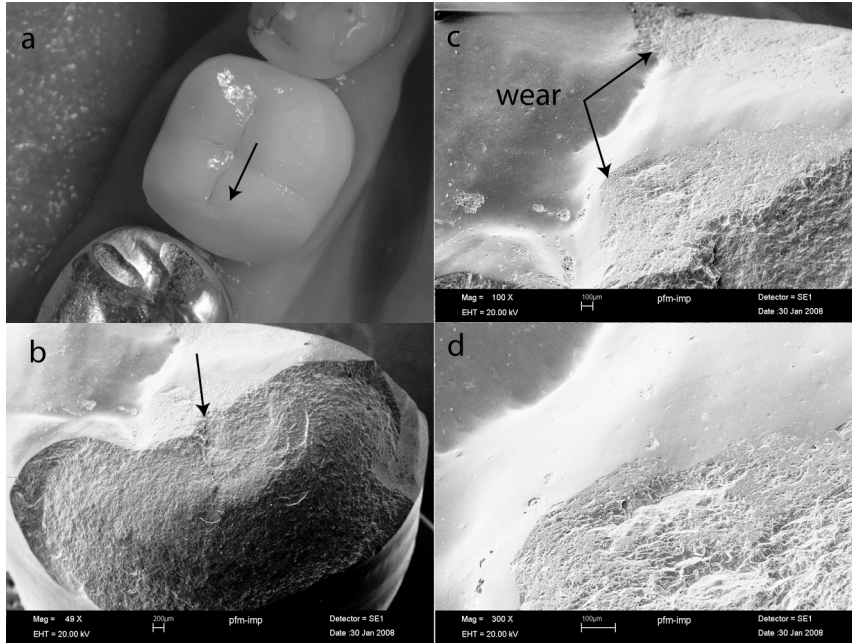


Figure 2. Porcelain-fused-to-metal chip failure after one year. (b) is a SEM image of the retrieved crown at low magnification and shows a compression curl on the bottom and sides of the photo in the form of a shoulder on the outer contour of the broken surface. The crack origin as indicated by the black arrow is located on the occlusal (i.e., chewing) surface next to a contact wear area (c,d).

Case 3 (Fig. 3): Chipping after 2 months of the feldspathic porcelain of a porcelain-fused-to-metal crown on a lateral incisor, cemented over a dental implant. The SEM images (Figs. 3b, 3c) were taken from a replica. A compression curl is visible in form of a shoulder on the outer contour of the broken surface. The crack origin (black arrows) located on the palatal (i.e., chewing) surface shows two blunt indents resulting from contact damage with the lower incisor (Fig. 3d, black arrow)

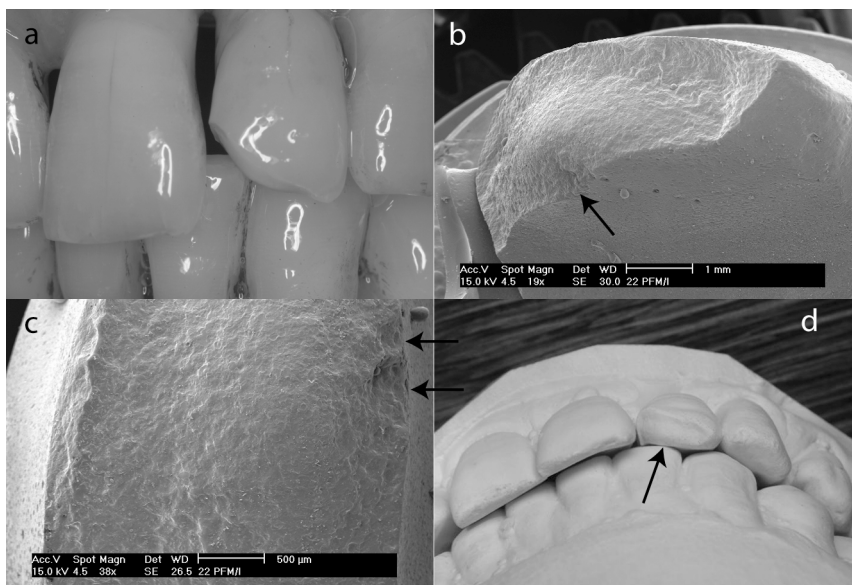


Figure 3. Fracture of the veneering ceramic of a porcelain fused to metal lateral incisor restoration. The SEM images in (b,c) obtained from a replica of the fractured surface, show a compression curl in form of a shoulder (on the opposite side away from the arrows) and two blunt indents (black arrows) corresponding to the fracture origin and resulting from contact damage with the lower incisor (d, black arrow).

Case 4 (Fig. 4): Chipping of the aluminous porcelain veneer of a Cerestore® lateral incisor crown after 58 months in service. The SEM images obtained from a replica show two major fracture facets including many arrest lines and hackle. The important palatal wear surface of the entire incisal edge is directly in contact with the origins (black arrows), and indicates major grinding habits with the lower teeth.

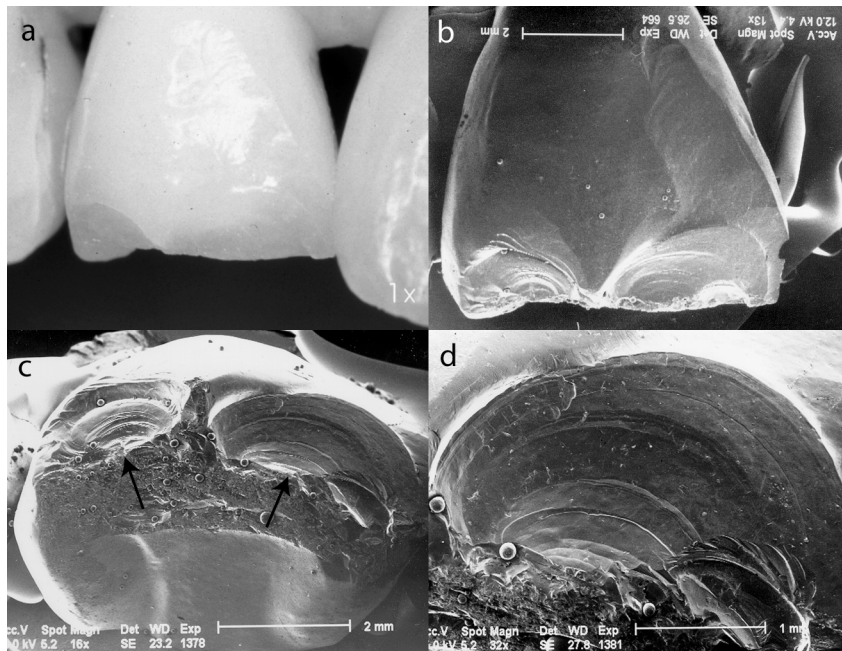
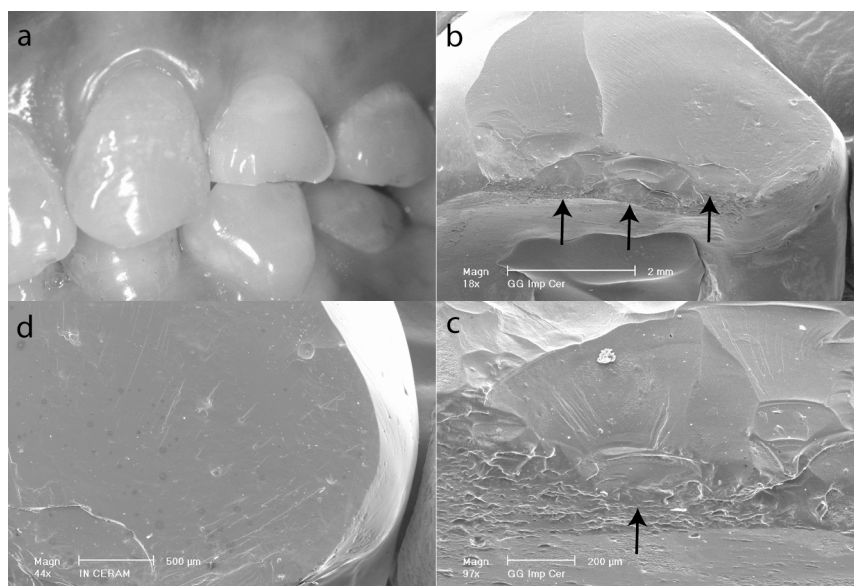


Figure 4: Chipping of the aluminous porcelain veneer of a Cerestore® lateral incisor crown after 58 months in service. The SEM images (b,c,d) obtained from a replica show two major fracture facets including many arrest lines and hackle. The important palatal wear surface of the entire incisal edge is directly in contact with the origins (black arrows), and indicates major grinding habits with the lower teeth.

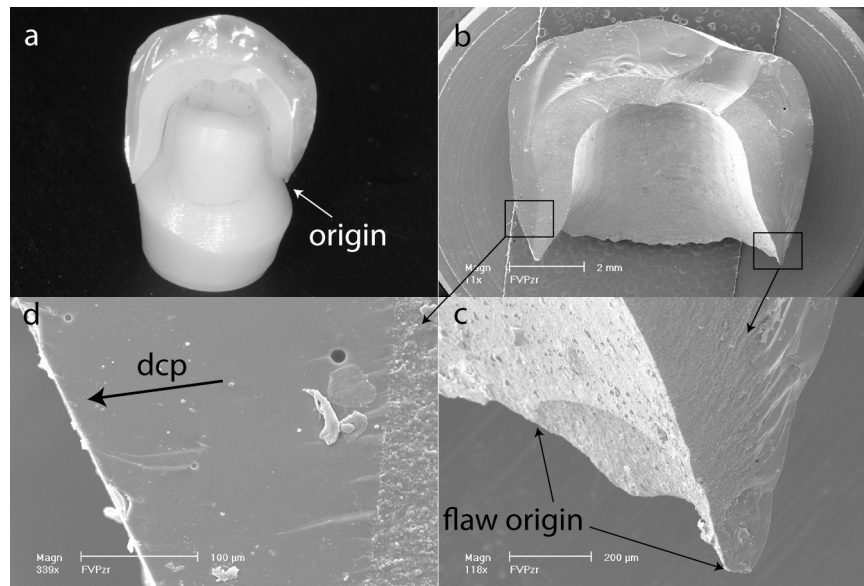
Case 5 (Fig. 5): Veneer ceramic edge chip of an In-Ceram Zirconia premolar crown, screwed over a titanium dental implant. The fracture occurred after 2 months of intraoral service. The SEM images are taken from a replica. Clear signs of wear at the incisal edge are visible (Figs. 5b,c), followed by several arrest lines. Multiple origins (black arrows) are seen located along the fractured edge (Fig. 5d) indicate the general direction of crack propagation running from the incisal edge (bottom of image) upwards, towards the gum.

Figure 5. Veneer ceramic fracture of an upper first premolar. Hackle and wake hackle (d) indicate the upwards direction of propagation. Several origins (black arrows) are located along the fractured edge (b). (c) is a higher magnification of (b) and shows a detailed region of the fractured edge near the first left arrow and contact wear, arrest lines, and hackle are seen.



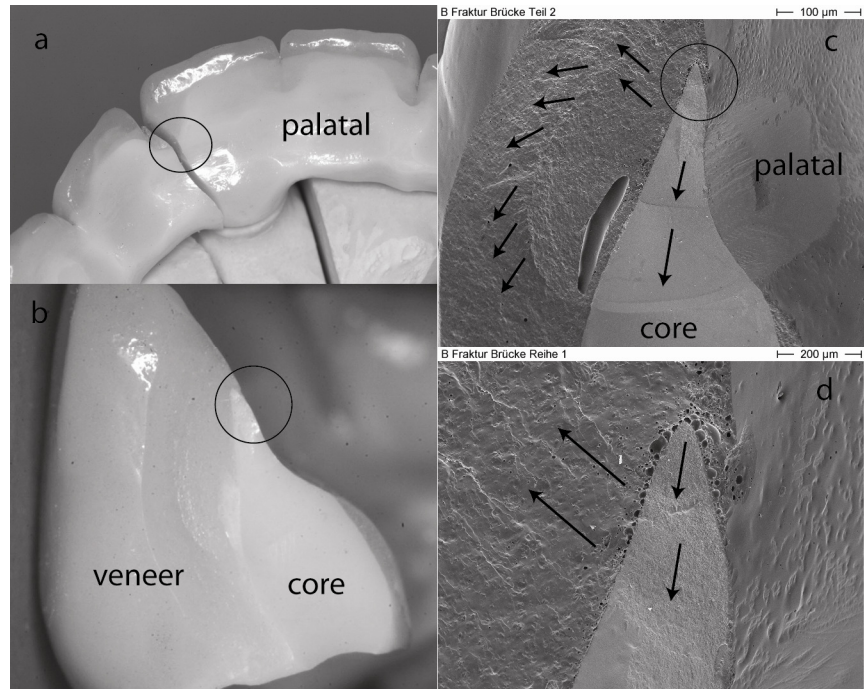
Case 6 (Fig. 6): Try-in failure through the alumina core of a Procera®AllCeram premolar crown over a zirconia implant abutment. The recovered fractured part (Fig. 6a) was analyzed in the SEM and showed many beautifully recognizable fractographic features such as hackle, wake hackle, arrest lines and compression curl. The flaw origin was located on the distal crown margin (lower right) as seen in Fig. 6c. The glassy composition of the veneering ceramic nicely reveals wake hackle (Fig. 6d) running outwards in the local direction of crack propagation (dcp) on the compression curl side. Additional damage then occurred on the inner crown surface of the alumina core as a result of the crushing impact with the zirconia abutment while the crown was breaking from the first crack and the patient kept pressing on the crown vertically (top of Fig. 6b). The primary cleavage plane runs from bottom right (distal margin) to left (mesial) (Figs. 6a,b).

Figure 6. Procera®AllCeram alumina core crown with its glassy veneering ceramic positioned over a zirconia implant abutment (a). A compression curl (left side) as well as arrest lines and hackle are clearly visible on the SEM overall image (b). A higher magnification of the lower right margin (c) shows the critical flaw that caused the failure. On the opposite margin (left) a higher magnification (d) shows several wake hackle lines within the glassy veneering ceramic confirming that the direction of crack propagation (dcp) was outwards on the side of the compression curl.



Case 7 (Fig. 7, next page): Fracture of a Cercon (Y-TZP) zirconia 6-unit bridge after 24 hours of intraoral use. The fracture through the core occurred at the connector between the central incisor and the lateral incisor (Figs. 7a,b). The low magnification SEM image (c) shows arrest lines within the zirconia core as well as hackle and wake hackle within the veneering ceramic indicating the direction of crack propagation as marked by the black arrows. Figure 7d is a higher magnification of the circled area in Fig. 7c representing the tip of the zirconia core surrounded by a cluster of pores within the veneering ceramic at the interface. This was starting point of the critical crack which then propagated downwards and outwards (black arrows).

Figure 7. Fracture of a Cercon (Y-TZP) zirconia 6-unit bridge. The fracture through the core occurred at the connector between the central incisor and the lateral incisor (b). The low magnification SEM image (c) shows arrest lines within the zirconia core as well as hackle and wake hackle within the veneering ceramic indicating the direction of crack propagation as marked by the black arrows. (d) is a higher magnification of the circled area in (c) representing the tip of the zirconia core surrounded by a cluster of pores within the veneering ceramic at its interface. This was starting point of the critical crack while it propagated downwards and outwards (black arrows). Original images are the courtesy of Dr. Ulrich Lohbauer (Univ. of Erlangen, Germany)



Discussion

The descriptive fractographic analyses of five ceramic veneer fractures as well as two through the thickness core fractures of clinically failed restorations identified the causes of failure and the origins. Thus, for all veneer chip failures, an origin located on the occlusal chewing side of the crown was identified. These veneer chip failures are due to a combination of problems. First, the glassy veneering ceramic is rather weak with low fracture toughness (i.e., $\approx 1 \text{ MPa}\sqrt{\text{m}}$) and low flexural strength ($\approx 100 \text{ MPa}$). Second, the veneering ceramic should be fully supported in all three dimensions by the stronger and tougher core materials such as alumina or zirconia. This is not always the case as these restorations have to be created in the laboratory with a perfect knowledge of the anatomical volume that is being restored. If too much veneering ceramic exists without an adequate core support, a crack may easily propagate under every day peak loading events. Third, the chewing paths and pressure on the restoration under function have to be perfectly adjusted by the clinician so that no overloading may occur. Veneer chips unfortunately result most of the time from a combination of one or all of these problems that have been insufficiently taken into consideration. The lessons learned from these chip failures are: 1) emphasize to the dental laboratory that correct three-dimensional constructions of the core materials are needed in order to properly support the veneering ceramic and, 2) dentists should carefully check the clinical contact loading points on the restoration during function and erase those located in critical areas such as the marginal ridges.

The fracture of the alumina crown during try-in (case 6) was a surprise as it came during the occlusal adjustment session with a patient using moderate biting force. The location of the origin at one margin can be explained by the fact that the alumina core was only $100 \mu\text{m}$ thick at the margins, which is an area of maximum tensile stresses, and that the crown was not yet cemented to the zirconia implant abutment during the biting adjustments. The lessons learned from this case are:

1) the core margins should be designed to be as thick as possible, and 2), dentists should permanently cement the crown onto the implant abutment before the final occlusal adjustments in order to reduce the stress concentration within the margins.

Finally, the connector fracture of the 6-unit zirconia bridge (case 7) showed several design problems. First, the zirconia core framework was anatomically wrongly designed in a drop shape that was not proportional to the volume to be replaced. Second, the whole zirconia framework was located too much on the palatal side, with a direct exposure to the occlusal contact surface with not enough space for the veneering ceramic. Third, the tip of the zirconia framework was so thin (100-200 μm) that the application the veneering ceramic was flawed so that there were many pores at the interface. This weakened the structure in an area exposed to chewing and pressing forces which created stress concentrations at the tip of the zirconia frame. The construction of a six-unit bridge involving many working hours, this fracture case should serve as a teaching lesson for laboratories to emphasize the importance of design issues as well as for clinicians to learn to recognize faulty design frameworks from laboratories.

Overall, fractographic analysis of clinically failed restorations should be done routinely in every dental school. Clinicians and dental students should be shown how to document and collect fracture parts without damaging the fracture surface. They should be shown how to use the replica technique for preserving fractographic information for analysis. Hopefully, dental fractography will help to understand the mechanisms of fracture and add to the accumulated clinical experience of failures, so that improved, more durable restorations can be designed and fitted.

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