Restorative dentistry done digitally
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CHAPTER 03

Fractography of clinically fractured, implant-supported dental CAD/CAM polymer crowns

• PART C •

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Fractography of clinically fractured, implant-supported dental CAD/CAM polymer crowns

Abstract

Today, a substantial part of the dental crown production uses CAD/CAM technology. A recent step in restorative dentistry is the replacement of natural tooth structure with pre-polymerized and machined resin based methacrylic polymers. The advantage of this approach is found in the adapted abrasivity and resilience in the context of physiologic function. However, those materials enter the dental market easily as medical products without extensive clinical or in vitro test results. Market approval is given by the fact that similar materials have been successfully introduced. But material properties are unique and cannot be generalized or transcribed to new materials. Recently, a new CAD/CAM polymer was launched for the crown indication, but the clinical reality forced the manufacturer to withdraw this specific indication.

The fragments of three fractured crowns were fractographically examined. They were cleaned in an ultrasonic alcohol bath for 5 minutes, observed under a stereomicroscope (SV6, Zeiss) and photographed with standardized illumination and equipment (Nikon D100, Medical-Nikkor 120mm, Nikon). The fractured crowns were coated with gold for examination under a scanning electron microscope (SEM) (Leitz ISI SR 50, Akashi, Japan). The fractographic examination was conducted using a systematic approach and interpretations of the fracture patterns were based on established fractographic methods. Arrest lines, hackle, wake hackle, compression curls and characteristic features were identified in order to trace back crack origins, propagation direction and discriminatory indicators of crack initiation or acceleration mechanisms. Wear facets and the exposed fractured surfaces were cautiously examined for core baring and cracking using SEM standard and back-scattered modes. Analysis regarding the presence of silica on the exposed implant surface was performed using XRD and Raman spectroscopy. Water sorption was measured according to ISO 4049.

The aim of the case series presented in this paper was to identify failure reasons for this CAD/CAM polymer material (Lava Ultimate, 3M Oral Care, USA) via fractographic examinations.
A major advance in digital restorative dentistry is the recent marketing of Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) polymer materials for single crown restorations. CAD/CAM polymers such as Lava Ultimate (3M Oral Care, USA) are in fact resin composites and are generally identified as highly filled methacrylic resinous materials. Anorganic nanofiller technology enabled a filler loading up to 82 vol% in a three-dimensionally crosslinked polymer matrix consisting of short and long chain dimethacrylate monomers. In the last two decades mechanical properties of such materials were improved competing today with silica based glass-ceramics for the single crown indication. While dental composites have traditionally been applied in a direct way – via viscous paste insertion, intraoral shaping, and subsequent light curing – the idea became appealing to further improve the mechanical performance by pre-polymerization. With the aid of pressure, temperature and suitable imitator system, and accompanied by the parallel development of high precision CAD/CAM technologies for dentistry, CAD/CAM polymers entered the market. The new CAD/CAM polymer materials are suspected to combine a sufficient high flexural strength with a relative low elastic modulus. They are supposed to mimic the resilient Periodontal Ligament by using a resilient crown material and hence to prevent biomechanical complications during occlusal contact loading. The improved resilience and enamel-like wear behavior, combined with the CAD/CAM chairside treatment option made this a popular material, very competitive and advantageous to established ceramic restoratives.

CAD/CAM polymer blocks are classified as medical products which allows marketing without proof of effectiveness from extensive clinical trials. It became obvious that a variety of such materials entered the market with different promises and performances. One of the first materials on the market was Lava Ultimate indicated for all types of single tooth restorations including the single full crown. After clinical use, the number of concerns increased in terms of fracture and debonding. However, the etiology of those incidences remains still unclear. A variety of combinations regarding support material (dentin, enamel, implant titanium or zirconia, etc.), adhesive procedure (surface pretreatment, bonding and cementation strategy, polymerization, etc.), and material degradation (hydrolysis, mechanical fatigue and wear, etc.) are currently under discussion in dental research. Basis of all those considerations is the knowledge of the exact fracture process: the adhesive compartment was identified as the weakest link. Adhesion is established by a complex luting multilayer, consisting of the crown and abutment material surfaces, the thin adhesive layers and the resin based luting cement in between.

The aim of this study was to analyze the clinical fracture process of 3 Lava Ultimate crowns, bonded to a zirconia implant abutments. All fractures occurred during the first year of function and within a randomized controlled clinical trial (RCT). Fractographical analysis was performed on the crown material as well as on the zirconia implant abutments in order to speculate on possible reasons for failure.
Materials and Methods

The fractographic examination of three fractured clinical crowns is based on a RCT. Although the clinical procedure is described elsewhere, a brief description relevant for the fractographic examination is as follows:

The restoration material used in both treatment modalities of the RCT was a resilient (“shock-absorbing”) crown material (based on resin composites) bonded to a stiff zirconia implant abutment. 50 patients with a missing single premolar in the maxilla or mandible were included. Amongst other factors, severe bruxism was rated as an exclusion criterion. After implant therapy and impression-taking, the abutment-crown-complex was fabricated in the dental laboratory. The zirconia abutment surfaces as well as the crown intaglio sides were sandblasted using the Rocatec system (tribochemical silica-coating using Rocatec Soft (3M Oral Care), 30µm, 2 bar, 2-10mm distance). The adhesive procedure made use of the 3M adhesive/cement system and was performed according to the respective instructions for use (IFU, in 2013). Scotchbond Universal (3M) was applied on the crown intaglio as well as on the abutment surfaces (no separate light curing, as stated in the IFU). RelyX Ultimate (3M) was used as resin luting agent and light cured for 5 min in a GC Labolight device (GC Europe, Belgium). After delivery, the crown-abutment-complex was screw retained to the implant and the access cavity was filled with a glass ionomer restoration material. 100% implant and abutment survival was evaluated, but only 14% (n=7) of the suprastructures showed uncompromised survival after one year of clinical service. 80% (n=40) initial debonded crowns and 6% (n=3) fractured crowns were documented. In all debonding cases, the luting remnants were found in the crowns but not on the abutment side, which was not always the case for the fractured crowns. The study was the first published clinical trial on the performance of Lava Ultimate restorative material.

The fragments of the three fractured crowns were collected and cleaned in an ultrasonic alcohol bath for 5 min and stored dry prior to further observation. The fragments were photographed with standardized illumination and equipment (Nikon D100, Medical-Nikkor 120mm, Nikon) and observed under a stereomicroscope (SV6, Zeiss) using lateral illumination. The fractured crowns were then coated with gold for examination under a scanning electron microscope (SEM, Leitz ISI SR 50, Akashi, Japan). The fractographic examination was conducted using a systematic approach and interpretations of the fracture patterns were based on established methods. Arrest lines, hackle, wake hackle, compression curls or any other characteristic features were identified in order to trace back crack origins, propagation direction and discriminatory indicators of crack initiation/acceleration mechanisms. Wear facets and the exposed fractured surfaces were cautiously examined using SEM standard and back-scattered modes. Analysis regarding the presence of silica on the fracture surfaces of the zirconia implant was performed using Energy-dispersive X-ray spectroscopy (EDS) and Raman spectroscopy. Water sorption of the crown material was measured according to ISO 4049.
Case 1
This crown was retrieved from tooth #14 of a 60 years old male patient and fractured after 2 month in situ without any complications or reported malfunction. The fractographic examination is presented in figures 1 and 2.

Case 2
This crown was retrieved from tooth #25 of a 39 years old female patient and fractured after 5 month in situ without any signs of malfunction. The fractographic examination is presented in figures 3 and 4.

Case 3
This crown was retrieved from tooth #35 of a 24 years old male patient and fractured after 4 month in situ. The patient reported that he felt loosening of the crown before mastication fracture. The fractographic examination is presented in figures 5 and 6.
Figure 1

Figures 1a-d show photographs of the crown and the abutment. The crown fractured mesio (m)-distally (d) in two fragments while some minor fragments on the mesial side went missing, most likely during intraoral fracture. Luting remnants can be found on the implant abutment surface (1b). Figure 1d shows the screw hole clinically filled with glass-ionomer cement (asterisk). Figure 1e/f present higher resolution SEM images (mapped from individual SEM images) from the fracture surfaces of the fragments shown in figure 1a/c. Both fragments exhibit the corresponding compression curl (circle), indicating the termination of the fracture event. The palatal fragment (figure 1e) shows clear fracture patterns on the cusp of the mesial proximal ridge (asterisk 1) and on the intaglio side of the disto-buccal margin (asterisk 2). The buccal fragment shows only minor luting remnants on the intaglio side (arrow). Most of the yellowish luting remnants are found on the zirconia abutment (figure 1b), indicating the crown-adhesive interface as the weakest link. In consequence, it seems very likely that the crown fracture was preceded by a debonding event, most likely leading to wedging of the crown and subsequent inclined shear loading in the direction assigned in figure 1e (dotted arrows). The fracture origin on the mesial intaglio surface e (asterisk 2) is thus termed a secondary event leading to abfraction of the missing marginal fragment. The general direction of crack propagation (dcp) is indicated with arrows on figure 1e. The fracture started on the mesial side and ended on the disto-buccal side.
Figure 2
Figure 2a shows the fracture origin on the palatal fragment of figure 1e (see asterisk 1). A large wear facet and damage accumulation zone can be seen on the surface (asterisk) as well as multiple and overlaying mist and hackle regions and radial crack extension (arrows). Figure 2b shows a magnification of the compression curl of figure 1e-f, the endpoint of the fracture event on the disto-buccal side of the crown. Figure 2c shows a high magnification of a fracture region close to the compression curl in figure 2b. Small cracks are observable hypothesizing a degradation artefact in the microstructure of the resin composite crown material. Figure 2d shows the secondary fracture event. Hackle indicate the dcp (arrows) radial from the fracture origin. Figure 2d further exhibits a clean intaglio surface (asterisk) without any remnants of the luting agents, indicating an adhesive failure at the crown-adhesive interface.
Figure 3
Figures 3a-d show photographs of the crown and the implant abutment. The crown fractured mesio (m)-distally (d) in two fragments. The zirconia abutment was found free of luting remnants (figure 3b). Figure 3d shows the screw hole clinically filled with glass-ionomer cement (asterisk). Figure 3e-f present higher resolution SEM images (mapped from individual SEM images) from the fracture surfaces of the fragments shown in figure 3a-c. Both fragments exhibit the corresponding compression curl on the mesial margins (circles), indicating the termination of the fracture event. On the opposite (distal) margins, figure 3e and f show a sharp and tilted fracture plane, suggesting the fracture initiation site at the marginal ridge (asterisks). A clear fracture origin cannot be located, but fine hackle lines trace back to the marginal ridge, as shown in figure 4d. Luting remnants can be found only on the crown intaglio surface as indicated by the arrows in figure 3e, indicating the zirconia-adhesive interface as the weakest link. It is likely that the fracture was preceded by a debonding event, resulting in tilting of the crown and shear fracture originating from the crown margins. The general direction of crack propagation (dcp) is indicated by arrows on figure 3f. The fracture started on the distal side and terminated on the cervical mesial margin.
Figure 4
Figures 4a-d present high resolution SEM images from the luting layer (figure 3a-b), the compression curl (figure 3c) and the fracture initiation site (figure 3d). While figures 3a-b are taken from the palatal fragment, figures 3c-d are taken from the buccal fragment. Figures 3a-b clearly show the adhesive layer on the zirconia-adhesive side as well as on the crown-adhesive side with the sandwich luting agent in between (see asterisks in figure 4b). The dcp can be seen from fine hackle lines, especially in the smooth and flat adhesive layer, indicated by arrows in figures 3a-b. Figures 3c-d also show the luting layer and the dcp, indicated by arrows. An overview of the general dcp is shown in figure 3f.
Figure 5
Figures 5a-b show photographs of the retrieved fragments. The crown fractured mesio (m)-distally (d) in two fragments. The corresponding abutment was not available for fractographic analysis due to further patient treatment. Figure 5c shows the occlusal view on the crown with the screw hole filled with glass-ionomer cement (asterisk) and the fracture plane eccentrically located on the lingual side, separating the lingual cusp (arrow). Interestingly, the fracture started on the massive and bulky lingual cusp which indicates an unbalanced masticatory loading. Figures 5d-e present higher resolution SEM images (mapped from individual SEM images) from the fracture surfaces of the fragments shown in figures 5a-b. Both fragments exhibit the corresponding compression curl on the distal side (circles), indicating the termination of the fracture event. On the opposite (mesio-lingual) side, figure 5d clearly shows the fracture origin (asterisk 1). A secondary fracture event is further located on the inner plane on the gingival third of the distal margin (asterisk 2). Fine hackle lines, especially in the adhesive layer (see further analysis in figure 6) trace the general dcp as indicated in figure 5e. The fracture started on the mesio-lingual cusp and terminated on the distal side. Luting remnants can be found on the crown intaglio surface. Some remnants broke off, as shown in figure 5d (arrow) and 5e (asterisks). The luting layer tends to delaminate from either the crown or the zirconia abutment. In principal, both adhesive interfaces (but predominantly the adhesive-zirconia interface) represent the weak link leading to crown debonding.
Figure 6
Figures 6a–e represent high resolution SEM images from the fracture origin (figure 6a) luting layer (figure 6b–e), the compression curl (figure 6f). While figure 6a is taken from the buccal fragment, figures 6b–f show magnifications of the lingual fragment. Arrows indicate the dcp in figures 6a–b, d, f. Figure 6a clearly shows the fracture origin with a fracture releasing subsurface defect (asterisk) and the radial fracture mirror and hackle region. The microstructure of the resin based crown material did not elucidate distinct fractographic patterns. The smooth adhesive layer on the other hand clearly indicates the dcp as shown in figure 6b. Parallel, crazing-like hackle lines are found. Figure 6c shows the delamination of the luting layer mainly from the zirconia abutment, but also from the crown surface (arrows). Also the microstructure of the luting agent indicates the dcp as shown in figures 6d–e. A magnification of the microstructure in figure 6e exhibits gull-wing like microstructural features indicating the dcp. The compression curl as the endpoint of the fracture event is shown in figure 6f.
Discussion

Based on the fractographic analysis, the crowns debonded most likely prior to the fracture event. This seems even more likely due to the fact that 80% of the crowns debonded from the zirconia implant abutment. Interestingly, the weakest link leading to debonding was identified either at the zirconia implant – adhesive or at the adhesive – crown interfaces. A clear conclusion cannot be drawn from the three cases. However, supported by the clinical observations, the zirconia-adhesive interface seems to be more relevant for the debonding event. A cohesive fracture within the luting agent has not been observed and can thus be excluded.

The used adhesive has shown sufficient bonding performance to both the resin based composites and to zirconia surfaces. Previous research has indicated that the reasons for the debonding can be manifold. Some of the potential causes are water uptake of the polymeric crown material, insufficient polymerization of the adhesive beneath an opaque crown or false marginal design or fit of the crown. The adhesion performance to zirconia and the hydrolytic changes of the resin based crown material are relevant for the current study. Based on the retrieved fragments the zirconia abutment surface was further chemically analyzed using Raman spectroscopy and the hydrolytic degradation of the crown composite was measured according to ISO 4049.

In order to establish a durable bond to zirconia surfaces, two approaches are clinically applied: chemical bonding via functional phosphate ester monomers or functionalization via tribochemical silica coating with subsequent silanization of the silica sites. The clinical procedure provides specific silanes for silica surfaces and specific zirconia primers containing functional monomer such as 10-methacryloyloxydecyl dihydrogenphosphate (MDP). The RCT which this case study refers to involved both approaches, i.e., tribochemical coating the zirconia abutments with alumina coated silica particles and the use of functional monomers. figure 7 shows the surface analysis of the zirconia implant abutment exhibiting clear, rough patterns of an air abraded surface but no indication for silica.

Figure 7
Analytical investigations on the buccal side of one debonded zirconia implant abutment (a). SEM surface reveals rough patterns due to sandblasting (b). EDS analysis did not show signs of silicon in the region of interest (c). The Raman spectrum did only indicate tetragonal zirconia and no signs of silica (d).
This has been analyzed using SEM-EDS and verified using Raman spectroscopy analysis. The Raman spectrum in figure 7 confirms the existence of tetragonal zirconia but no indication for silica on the buccal side of the implant abutment. Also EDS reveals no remnants of silica. However some alumina has been found attached on the zirconia surface. Due to the lack of silica on the zirconia surface, one should conclude that adhesion is compromised.

The load-bearing capacity and load transfer through the whole system during mastication are also interesting to note regarding this specific crown–implant configuration. The elastic properties of the involved materials ($E_{\	ext{Lava Ultimate}}$; 11 GPa; $E_{\	ext{Luting agent}}$; 6 GPa; $E_{\	ext{Zirconia}}$; 208 GPa) imply that the luting composite has to bear most of the occurring stress during functional chewing. The damping behavior of the natural periodontal ligament is replaced by a osseointegrated titanium implant. Adding up to this localized stress state, a resin based methacrylic composite is known to take up water over time and to suffer from hydrolytic degradation and dimensional swelling to a certain extent. Figure 8 shows a water saturation plot of the crown material under investigation.

**Figure 8**

Water saturation curve for the resin based composite Lava Ultimate over two month water storage period according to ISO 4049. The material absorbed 43 µg/mm³ water.

The material takes up a maximum of 43 µg/mm³ water over two month saturation period. The 95% water saturation level is already reached after 14 days of water storage. The maximum of 43µg/mm³ actually exceeds the maximum threshold value (40 µg/mm³) reported in ISO 4049 for polymer-based
filling, restorative and luting materials. Although not measured, a relative dimensional change of a clinically placed crown can be concluded, based on the high amount of absorbed water, in turn increasing the stress state at the interface between crown and the zirconia abutment. Dental literature has not paid much attention to the swelling of the resin luting agent, but indications are available that the hydrolytic expansion stress might be responsible for crown fractures.

**Conclusions**

In combination with a preceding clinical trial, this fractographic case series underlined the debonding of the resin based crowns from the zirconia implant abutments being the central reason for fracture. The adhesive interface was identified as the weakest link. A lack of silica at the zirconia surface might have compromised the bonding potential of the adhesive system from the beginning. Additionally, the hydrolytic stress released from swelling of the resin based crown and transfer to the luting interface further added to the interfacial stress and most probably contributed to the debonding failure.

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