Fractography

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Abstract

The biomechanical perspective of fracture predilection in post-core restored teeth is investigated using computational, experimental, and fractographic analyses. The computational finite element analysis and the experimental tensile testing are used to evaluate the stressstrain response in structural dentin. The fractographic evaluations are conducted using laser scanning confocal microscopy and scanning electron microscopy to examine the topography of dentin from fractured specimens.

Keywords: crack propagation; dentin ; stress; strain; fractography

Introduction

The study of fracture surfaces has been practiced for centuries with the first written description of cleavage of calcite in 1688 and further applications to metals and their alloys in the 17th and 18th centuries. Over the centuries, fractography has flourished in fields such as geology; much of the current nomenclature is derived from geological terminology. Fractographic methods are routinely used to determine the cause of failure in engineering structures, especially in product failure and the practice of forensic engineering or failure analysis. In material science research, fractography is used to develop and evaluate theoretical models of crack growth behavior.

Failure Theories

Static stress means that the stress has been applied slowly and is maintained at a steady level. There are many other factors such as, surface wear damage from friction, overheating, chemical corrosion, metallurgical fault or a combination of these and others that may also cause failure. There are four important failure theories, namely (1) maximum shear stress theory, (2) maximum normal stress theory, (3) maximum strain energy theory, and (4) maximum distortion energy theory. Out of these four theories of failure, the maximum normal stress theory is only applicable for brittle materials, and the remaining three theories are applicable for ductile materials.

Maximum Shear stress Theory- This theory postulates that failure will occur in a machine part if the magnitude of the maximum shear stress in the part exceeds the shear strength of the material determined from uniaxial testing.

Maximum normal stress theory- this theory postulates, that failure will occur in machine part if the maximum normal stress in the part exceeds the ultimate tensile stress of the material as determined from uniaxial testing.

Maximum strain energy theory-this theory postulates that failure will occur when the strain energy per unit volume due to the applied stresses in a part equals the strain energy per unit volume at the yield point in uniaxial testing.

Maximum distortion energy theory- this theory is also known as shear energy theory or von Mises-Hencky theory. This theory postulates that failure will occur when the distortion energy per unit volume due to the applied stresses in a part equals the distortion energy per unit volume at the yield point in uniaxial testing. Out of the four theories, only the maximum normal stress theory predicts failure for brittle materials. The rest of the three theories are applicable for ductile materials. Out of these three, the distortion energy theory provides most accurate results in majority of the stress conditions.

An important aim of fractography is to establish and examine the origin of cracking, as examination at the origin may reveal the cause of crack initiation. Initial fractographic examination is commonly carried out on a macro scale utilising low power optical microscopy and oblique lighting techniques to identify the extent of cracking, possible modes and likely origins. Optical microscopy or macrophotography are often enough to pinpoint the nature of the failure and the causes of crack initiation and growth if the loading pattern is known.

Dentin

Dentin in the outer part of the tooth exhibites a smooth cleavage plane, which is characteristic of brittle fractures, while dentin in the inner part of the tooth in proximity to the root canal exhibited a corrugated and tearing pattern; this could be termed quasibrittle or ductile behavior. The outer dentin peritubular dentin that is highly mineralized exhibited a brittle mode of fracture propagation,whereas the inner dentin mantle dentin, which is less mineralized exhibited the ductile mode of fracture propagation. Subsequently, the brittle dentin in the outer part would offer less resistance to fracture propagation compared to the inner dentin. It is essential to note that earlier studies of bones have demonstrated an association between a high degree of mineralization and low values of work of fracture which is a measure of fracture toughness and vice versa. The low fracture toughness associated with the high degree of mineralization was caused by the inhibition of various crack-stopping mechanisms with a high volume fraction of

minerals.Tooth loses core dentin material due to both the disease process and the treatment procedure. Subsequently, when the tooth is restored using postcore restoration, it is observed that the postcore tooth system bends like an integral unit along with the remaining dentin structure during function and thereby alters the nature of the stress distribution within the existing tooth structure. Consequently, high tensile stress and stress concentrations are produced in the remaining dentin structure . Further,the fractographic analysis has shown that the highly mineralized outer dentin exhibits a conspicuously brittle mode of fracture propagation that should offer less resistance to fractures. This will cause the postcore restored tooth to become weak. It is suggested that, in order to obtain postcore restoration that substitutes tooth strength to its "near" original state, it is important to engineer endodontic postcore restoration that does not induce stress concentrations and high tensile stress for the remaining dentin structure. Further, replacement of the lost inner, fracture resistant, ductile dentin with a suitable restorative material should also be considered.

Micromechanisms of Composite Failure

To undertake a fractographic analysis it is important to understand the basic failure modes in the constituent materials. However, composites fail in numerous different modes, all of which interact, the degree to which depends on factors such as loading conditions,material architecture, component geometry, environment, etc. These failure modes can be grouped into one of three classes; translaminar, interlaminar and intralaminar. Translaminar failure entails fracture of the reinforcing fibres and includes modes such as fibre cleavage, buckling and shearing. Interlaminar fracture of brittle matrices is governed by mechanisms such as localized cleavage, which manifests as “textured microflow”. Under loading normal to the laminate plane, localised crack fronts overlap and coalesce,leading to features such as riverlines, from which the crack propagation direction can be directly inferred, when either interlaminar or intralaminar shear stresses are introduced the crack planes reorientate,leading to the development of cusps from which information such as the mode mixity, direction of shear loading and crack growth direction can be gleaned. Fibers affects the fracture process which results in interrupting crack growth progression and thus enhances the fracture toughness of the FRC material. Structural flaws are always present in the resin matrix and under the influence of cyclic loading microcracks start to develop as the initial sign of failure.With the continuous loading and due to the effect of stress concentration at these structural defects microcracks start to grow and join each other to form larger cracks serving as an entrance for oral fluids and bacteria, which may further accelerates the failure process. Nevertheless, the restoration should be designed to bring the supporting fibers in tension in order to gain any strength benefit.[1]

Ceramic materials

Because of their brittle nature, ceramic materials are susceptible to failure from small flaws or cracks under applied tensile stresses. There are several factors which can be associated with crack initiation and propagation in dental ceramic restorations, including: (1) shape of the restoration; (2) microstructural inhomogeneities; (3) size and distribution of surface flaws; (4) residual stresses and stress gradients, induced by polishing and/or thermal processing; (5) the environment in contact with the restoration; (6) ceramic cement interfacial features; (7) thickness and thickness variation of the restoration; (8) elastic moduli of restoration components; and (9) magnitude and orientation of applied loads. The possible interactions among these variables complicate the interpretation of failure analysis observations. Fracture surface analysis has been used extensively to study the fractographic features of glasses, glass-ceramics,and single and polycrystalline ceramics (Frechette, 1990).These studies have identified a variety of fracture surface markings that characterize the fracture origin and the propagation path of the primary crack. The markings act as a detailed record of the fracture process. These studies have also shown the existence of four distinct regions surrounding the failure initiation site (primary flaw) in brittle materials: (1) the mirror region, (2) the mist region, (3) the hackle region, and (4) the macroscopic crack branching Region.

Observations

(1) Optical and SEM microscopic analyses of failed dental ceramics provide essential initial information on the origin of fracture and the magnitude of failure stresses.However, further information on fabrication damage conditions (grit-blasting pressure, abrasive used,particle sizes of abrasive diamonds, acid-etching procedure, if used, etc.) and occlusal status (normal, group function, bruxism, bite force capability, etc.) is needed for complete characterization of the failure process.

(2) Fracture initiation sites appear to be controlled primarily by the location and size of the critical flaw,and not by specimen thickness. It is hypothesized that specimen thickness plays a secondary role on fracture initiation except for the condition where the critical flaw is located in a region of reduced thickness.

(3) Improved imaging methods are needed to enhance the resolution of the critical flaw and other fracture surface features in non-glassy ceramic structures such as core ceramics of alumina or complex spinels. Other methods, such as

fractal geometry, may also be useful in quantitative assessments of fracture surface features in these materials, and possibly in determination of the failure stresses of restorations fabricated from these materials.[2]

Fractographic analysis of clinically failed dental ceramics can provide insights as to the failure origin and related mechanisms. One anterior 6-unit all-ceramic zirconia fixed partial denture (FPD) (Cercon) has been clinically recovered and examined using qualitative fractography. The purpose was to identify the fracture origin and to state the reasons for failure. The recovered parts of the zirconia FPD were microscopically examined to identify classic fractographic patterns such as arrest lines, hackle, twist hackle and wake hackle. The direction of crack propagation was mapped and interpreted back to the origin of failure at the interface of the occlusal-palatal tip of the core and the veneering ceramic.[3]

Mandelbrot was the first to use fractal geometry to explain the apparently random nature of fracture surface . The term "fractal" refers to the mathematical concept of how fragmented geometries can be subdivided in parts, each of which is a reduced size of the whole (self-similarity) . It means that if any portion of the surface is enlarged in scale, it would appear identical to the whole surface (scale invariance). In the area of material science, fractal concepts have been applied to analyze surface that are formed through a fracture process. Different materials usually exhibit different fracture surface features . In addition, materials with the same composition may demonstrate different fracture patterns depending on material microstructures, manufacturing processes and loading conditions .Correct fractographic interpretation,includes : (1) direct optical microscope observations at low angle incident lighting; (2) the viewing of stereo SEM pairs; and (3) obtaining comparative SEM photographs at different magnifications, tilts, contrasts and in back scattering mode.Fracture failures of dental ceramics can be associated with crack initiation and propagation in dental restorations . Fracture of ceramic FPDs tends to initiate in the connector area because of stress concentration and the radius of curvature at the gingival embrasure. Consequently, fracture propagates along the connector and leads to the failure of ceramic FPD .[4]

Fractographic analysis of indentation cracks is performed following flexure testing as part of the ASTM (1999) standard for fracture toughness. The fracture toughness test is based on the ASTM polymers standard (ASTM D5045) and the ASTM ceramics standard (ASTM C1421, precracked beam method).This method depends on the conduciveness of the material towards fractographic interpretation. In brittle materials such as ceramics, fracture begins from a single location called the fracture origin, which is a discontinuity such as a flaw or a defect that has developed from mechanical, chemical or thermal processes that will act as a localized stress concentrator. Under a specific critical applied stress, the crack will initiate from these defectsites and propagate, leaving characteristic markings on the fracture surfaces.Recently, the surface crack in flexure method (SCF) has been developed to be used as an ASTM standard for fracture toughness determination of advanced ceramics (ASTM C1421-99). This technique combines the use of a controlled surface flaw (indentation) with a conventional bending test after removal of the indenter's residual stress zone, and fractographic means to measure the crack dimensions on the fracture surface. Test methods are intended primarily for use with advanced ceramics which are macroscopically homogeneous. Certain whisker- or particle-reinforced ceramics may also meet the macroscopic behavior assumptions.[5,6]

Discussion

Fractography techniques may be helpful in determining the strength limiting features of resin composite clinical restorations as well. Also promising is the edge chipping test, which quantifies a material's hardness to a failure mode that is clinically relevant. Finally, hardness was found to be very load-dependent and comparisons of resin composites should be made over a clinically relevant load range, rather than at a single load.[6]

The results suggest that the geometry of the dento-osseous structures and the structural gradients at the tooth-bone interface play a significant role in the distribution of stresses without stress concentrations. Further, the application of an advanced image-processing system with the circular polariscope showed notable advantages and could be applied in other biomechanical investigations.[7]

Kishen et al. study comprised two parts: a photoelastic study and a fractographic analysis. They compared stress patterns induced in the photoelastic study with the plane of fracture in the fractographic analysis using mandibular incisors restored with ParaPost and composite core. A strong correlation was found between the photoelastic stress patterns recorded and the plane of fracture observed by SEM study [8].

Dentine is a porous hydrated composite structure that forms the major bulk of the human tooth. The hydrated dentine displayed significant increase in strain with stress in the direction perpendicular to the dentinal tubules, and this response was characteristic of a tough material .[9]

Photoelasticity is a useful technique for evaluating the stresses responsible for failure of a structure, especially one with

irregular form . This technique is a relatively qualitative visual measurement based on the ability of certain transparent materials to exhibit interference fringes when stressed in a field of polarized light. The distinct fringes illustrate zones of stress intensity and concentration with a sequence of colored bands . This technique has been used in several dental studies to analyze the stress distribution of various posts [10-14].

Engineering theory states that the strain in the material adjacent to a hole in a structure will be two or more times higher than the stress if the hole were not present. The increase in strain in the materials or in tissues around such a "defect" means that even a minimal stress concentration can initiate failure in these regions. It is crucial to understand that in a rehabilitated tooth much dentin material is removed from the core adjacent to the root canal during cleaning and shaping procedures of the root canal and post preparation. Consequently a root canal space, which is thin ribbon or oval shaped in cross section, is altered into a large round configuration. This causes a drop in fracture resistance in post and core restored teeth results. The ratio of the failure load of the altered structure to the failure load of the intact structure is said to be one measure of the reduction in structural strength. Hence it could be rationalized that there is a reduction in dentin strength due to dentin removal and restorative treatment procedures.

Future Issues

For the fractographic analysis of metal components, factors such as service temperature,severity of loading and cycles to failure can be quantified from the surface morphology. Crack velocity in rate sensitive materials such as thermoplastic composites, the stress at failure of corroded laminates or delamination development in laminates exhibiting ply splitting are all quantities which could potentially be determined directly from the fracture morphology.

To improve the value of fractographic techniques , there are a number aspects which still need to be addressed. The fibre/matrix interface is sensitive to environmental factors and will thus influence the fracture morphology. Therefore, components which have been exposed to temperatures or moisture excursions beyond their normal service conditions will exhibit 'cleaner' fibres, increased matrix ductility and increased fibre bridging between the crack faces . However, although such morphology is indicative of exposure to extreme conditions, it is difficult to relate the extent of these morphologies to the conditions to which the component has been exposed. Furthermore, evidence of exposure can only be deduced by comparing with fracture morphologies generated under ambient conditions.

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