Review

ADM guidance-ceramics: Fatigue principles and testing

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ABSTRACT

Background. Clinical failure of dental ceramics is usually reported as partial fracture of the restoration (chipping) or as catastrophic fracture of the whole structure. In contrast to metals, ceramics are linear-elastic, brittle materials exhibiting extremely low damage tolerance to failure. Well documented clinical and lab reports have shown this fracture event often occurs at loads far below their fracture strength due to intrinsic fatigue degradation via slow crack growth or cyclic fatigue mechanisms. The presence and development of surface flaws have a dominant role in damage accumulation and lifetime reduction of ceramic structures.

Aims. This ADM guidance document aims to summarize the aspects related to fatigue degradation of dental ceramics, reviewing the concepts of fatigue testing and furthermore aims to provide practical guidance to young scientists entering into fatigue related research. The description of fatigue strength is always accompanied by a clear understanding of the underlying fracture mechanisms.

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1. Introduction

The mechanical performance of ceramic materials is commonly approached by measuring the fracture strength or toughness using simplified bar or disc specimens. Such methods reflect the static, inert behavior of materials at critical loads, focusing on fracture as the final event. As fracture is the rupture of the bonds, fracture strength of ceramics is known to be inversely proportional to the largest or critical flaw present in the loaded volume, as described by Griffith’s law [1]. One can find detailed information on fracture strength and toughness in the corresponding ADM guidance documents (www.academydentalmaterials.org).

Any component in normal service is loaded far below its critical load either continuously or under repetitive conditions. The related mechanical phenomenon is called “fatigue”, which is often defined as the degradation (weakening) of a structural component under the influence of mechanical, chemical or biological stress – and in most cases – a combination of them.

The fatigue progression over time is shown in Fig. 1. At certain service loads (below the fracture strength), flaws (defects, cracks) tend to grow. As the stress intensity at the crack tip increases with growing flaw size, the relation between flaw size and service life becomes exponential. Depending on the level of applied service loads, the material strength drops significantly from the inert strength and a fatigue failure is expected. However, at low service loads, fatigue (or endurance) limits may exist at a stress below which no further crack growth happens and failure will not occur no matter how many loading cycles are involved or how long a component is statically loaded (threshold value).

In dentistry, one could think of a cyclic loading scenario in a compressive or bending configuration combined with the influence of water that simulates, in vitro, the clinical conditions of mastication. Degradation of properties always occurs over time, so the fatigue parameter actually reflects the time-dependency of material performance and in the end determines the lifetime of a restoration. While inert strength measurements investigate fast fracture, fatigue investigations

Fig. 1 – Relationship between flaw size, time in service and residual fracture strength. Induced by a combination of applied stress in a corrosive aqueous environment, a flaw grows with time to a critical size bringing about fatigue failure at a reduced stress level compared to the inert fracture.
deal with crack initiation and the slow growth of cracks under the influence of the environment. The fast fracture criterion is termed “critical” whereas the slow growth of cracks is called “sub-critical” crack growth (SCG) [2].

The definition of fatigue at ambient temperatures mostly involves two major, relevant mechanisms, arising either from stress corrosion (SCG) (chemically-assisted by water) and/or from additional cyclic effects [3,4]. While SCG has been demonstrated 70 years ago [5], in the past it was believed that there was no additional effect from cyclic loading in the fatigue behavior of brittle ceramics. Extensive research on the fatigue of metallic materials, showing that cyclic fatigue plays a dominant role, also led to insights into the damaging effect of cyclic loading for ceramics. In brief, while SCG might occur in a comparable rate independent from static, dynamic or cyclic loading, cyclic effects arise from friction and hydrolytic pressure during crack closing. Today, there is a common understanding that cyclic effects contribute to overall degradation of brittle ceramics, although to lesser extent compared to SCG [3].

Clinically, fatigue degradation over time is always associated with progressive surface wear (abrasion and attrition). During wear, an extended damage accumulation zone is formed on the surface with the largest defects further progressing to fatigue crack growth. A specific ADM guidance document reviewed the mechanisms involved in the intraoral wear process that controls mechanical strength degradation (www.academydentalmaterials.org).

This document seeks to provide an introductory guidance to the field of dental ceramics fatigue. The principles and mechanisms presented here are – within limitations – expandable to dental resin-based composites. For those readers interested in learning more about the principles behind slow crack growth, we suggest literature that provides more comprehensive coverage of the subject. For a general overview, there is an easy-to-read book recommended from Ashby and Jones on properties and applications of engineering materials. Parts D and E of this book introduce the principles of fast fracture, fracture toughness and fatigue and answers the most basic questions [6]. Fundamental studies on glass fatigue were published by Charles and co-workers [5,7,8]. Further reading especially on the fracture mechanics background of fatigue crack growth can be found in David Broek’s book entitled “The practical use of fracture mechanics” or in Dieter Munz and Theo Fett’s book “Ceramics” [9,10]. A more recent, comprehensive review on “Fracture of Ceramics” was published by Danzer et al. [3]. They comprehensively reviewed the concept of stress corrosion versus cyclic fatigue effects. Focusing on the aspects of ceramic fatigue related to dentistry, the book from Kelly [11] is recommended as well as the more recent and clinically oriented review from Zhang et al. [12]. Typical fracture modes, and fatigue mechanisms in clinical service are described and discussed. For an in-depth analysis of the fatigue responses of ceramics and constitutive models providing insights into fatigue processes the book from Suresh is highly recommended [13]. The principles and mechanisms responsible for fatigue of resin composite can be found elsewhere [14].

Based on ISO and ASTM standards, fatigue of metallic materials is well described but only little guidance is available on how to perform fatigue experiments on brittle materials. A Japanese standard introduces the static bending fatigue method for fine ceramics [15]. The ASTM-C-1368 standard is a comprehensive document describing the constant stress-rate method for evaluating slow crack growth parameters [16]. A comparable approach on dynamic fatigue is described in the European standard EN 843-3 [17]. The only advice related to dentistry can be found in ISO 14801 where cyclic fatigue testing of dental implants is described [18].

Of course, this guidance document cannot comprehensively cover all fields related to fatigue degradation, such as fracture toughness or increase of toughness with growing defects (R-curve behavior) [19,20]. Also, the influence of internal stresses on toughness and strength as well as related aspects of multilayered or graded components are not addressed here. Further reading is provided by ADM guidance documents on fracture toughness and multilayered dental ceramics (www.academydentalmaterials.org) [2,21].

2. General considerations

Damage accumulation after multiple cycles at low loads can alter the durability of ceramic parts, reducing their service life (Fig. 1). This is especially true for ceramic parts operating in wet environments. Chemically-assisted crack growth (SCG) is probably the most important (and most studied, either directly or indirectly) fatigue mechanism affecting all dental ceramics (see Table 1). This mechanism involves the slow growth of cracks at stresses and crack tip stress intensities well below those associated with catastrophic fracture. The hydrolytic principle leading to corrosive bond rupture and cleavage in glasses and ceramics is shown in Fig. 2.

Slow crack growth involves existing flaws and influences the behavior of especially feldspathic porcelains, glass-ceramics and polycrystalline ceramics. For all ceramics, there are stress intensities below which cracks will not grow (stress intensity factor threshold, Kθ). From a fracture mechanics standpoint, fatigue crack growth can be described as the relationship between the crack velocity, v, and the applied stress intensity Kc at the crack tip. Fig. 3 shows the slow crack growth parameters “n” and “A”, which are derived from fatigue crack growth experiments [10]. With increasing stress intensity, the curve shows a linear relationship with the increasing crack velocity (region I), described in the so called Paris law [22]:

\[ v = \frac{da}{dt} = A \cdot K_c^n \] (1)

Certain polycrystalline ceramics, such as transformation toughened zirconia and possibly some glass-ceramics can experience additional damage accumulation involving the development of internal volume flaws. For example, distributed microcracking along grain facets and/or interfaces has been documented. In non-cubic single phase ceramics (e.g., alumina, zirconia) and composites (e.g., glass-ceramics) residual stresses may develop at grain boundaries and composite phase interfaces during cooling that can lead to nucleation of microcracking under the influence of external stress. In transformation toughened ceramics (e.g., Y-TZP) microcracking occurs during the stress-induced martensitic
### Table 1 – Fatigue measuring techniques and their application.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Principle</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Crack growth experiments (direct method, pre-cracked components)</td>
<td>Visual crack growth tracking [20,63–67]</td>
<td>• Direct assessment of R-curve behavior</td>
<td>• Extremely difficult to observe high speed cracks in a brittle material</td>
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<td></td>
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<td>• Certainty of initial crack size</td>
<td>• Usually restricted to cyclic experiments</td>
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<td></td>
<td></td>
<td>• Requires fewer specimens</td>
<td>• Might require unloading for regular visual inspection</td>
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<td></td>
<td></td>
<td>• Allows identification of toughening mechanisms</td>
<td>• Usually runs under fixed stress amplitudes</td>
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<td></td>
<td></td>
<td>• Requires fewer specimens</td>
<td>• Use of long, less-relevant crack sizes</td>
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<td></td>
<td></td>
<td>• May use surface pre-cracks that are more strength relevant</td>
<td>• Crack size at the sides of the specimen misrepresent the real crack size in the bulk</td>
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<td></td>
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<td>• Gives precise account of first increments of crack size</td>
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<td>• May be conducted under constant K_{appl}</td>
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<td>• Taken as the gold standard of v-ΔK experiments</td>
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<td>Crack growth tracking via compliance [20,68]</td>
<td>Static fatigue [7,8,69–72]</td>
<td>• Uses natural flaws</td>
<td>• Requires a large amount of specimens</td>
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<td>• No need to produce an artificial sharp pre-crack</td>
<td>• Relies on the uncertainty of regression procedures</td>
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<td>• Easy to conduct</td>
<td>• Usually ignores the real (Weibull) strength distribution due to reduced amount of specimens per stress range</td>
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<td>• Needs simple equipment</td>
<td>• Uncertainty of initial crack size</td>
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<td>• Sensitive to surface residual stresses</td>
<td>• Sensitive to surface quality</td>
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<td></td>
<td></td>
<td>• Useful for constructing strength-probability-time (SPT) diagrams</td>
<td>• Stress-controlled instead of K-controlled</td>
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<td>Crack growth experiments (indirect method, natural flaw population)</td>
<td>Dynamic fatigue [36–39,42,73–76]</td>
<td>• Same as static fatigue</td>
<td>• Same as for static fatigue (data scattering is much lower)</td>
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<td>Cyclic fatigue [19,27,40,70,72,77]</td>
<td>• Accounts for cyclic effects that may degrade toughening mechanisms</td>
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<td></td>
<td></td>
<td>• Important parameters such as frequency and stress amplitude may be varied</td>
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<td>• More relevant for real world applications</td>
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<td></td>
<td>• May be devised to account for R-curve effects</td>
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<tr>
<td>Phenomenological approaches</td>
<td>S–N curve [41,72]</td>
<td>• Does not require sacrificial specimens to determine an appropriate stress level</td>
<td>• Difficult to establish the initial stress level for testing</td>
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<td>• Encompasses multiple stress levels</td>
<td>• Usually encompasses only one stress level</td>
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<td></td>
<td></td>
<td>• Gives insight on the existence and location of an endurance limit</td>
<td>• Requires appropriate equipment</td>
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<td></td>
<td>• Provides a fatigue parameter “n” likewise in crack growth experiments</td>
<td>• More complex statistical treatment to account for early fractures and run-out specimens</td>
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<td></td>
<td></td>
<td>• Able to distinguish between LCF and HCF</td>
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<td>Staircase approach [78–85]</td>
<td>• Can be performed with fewer specimens</td>
<td>• Requires a large number of specimens to be tested at different stress levels</td>
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<td></td>
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<td>• Provides accurate estimations of the mean fatigue strength</td>
<td>• Usually limited numbers of specimens are tested for each stress level</td>
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<td>• Relies on the uncertainty of regression procedures</td>
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### Table 1 (Continued)

<table>
<thead>
<tr>
<th>Principle</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Step-stress approach [50,86]</td>
<td>• Optimizes the time of testing</td>
<td>• Requires an analysis accounting for cumulative damage</td>
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<td>• Incorporates run-outs in the analysis</td>
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<td></td>
<td>• Employs varying stress amplitudes</td>
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<td>• May be used to estimate longer lifetimes</td>
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**Fig. 2** – The degrading influence of water on slow crack growth is explained by a corrosive, diffusion controlled attack of water molecules at the tip of a crack, hydrolyzing siloxane bonds (Si–O–Si). Under mechanical loads the Si–O–Si bonds are strained, which further accelerates the hydrolytic reaction (adopted from Refs. [5,7,8,31]).

**Fig. 3** – A principal v-K_f (crack velocity versus stress intensity in mode I) plot. The curve shows the onset threshold (K_0) of crack initiation, a stable, linear crack extension interval (region I) a plateau (region II) and the approximation towards fast fracture at the actual fracture toughness (region III, K_{IC}, adopted from Ref. [4]).

transformation creating the transformation zone around stressed cracks. Graphic examples of various types of surface flaws are presented in an ADM guidance document on clinical fractography (www.academydentalmaterials.org) [23].

### 3. Probabilistic nature of fatigue

The well-known fact that ceramic strength is sensitive to surface defects and their subsurface extension – the larger the flaw, the lower the strength of a ceramic – directs our attention towards the statistical distribution of flaws. Unfortunately, the specific distribution of a flaw population in a loaded volume often results in high scatter of the experimental data. Surface optimization (polishing) certainly provides more reliable data (and narrow distribution) but a robust statistical treatment of data remains mandatory. The use of Weibull statistics is by far the most applicable procedure for brittle ceramics [24]. Under fatigue conditions, surface defects are induced to grow slowly and data scattering gets even worse. Especially cycles-to-failure as a function of load experiments (S–N curve) exhibit non-normal failure distributions and are commonly treated by log-normal or extreme value distributions, or have been known to follow Weibull distributions. If the strength of a material is distributed according to the Weibull distribution one could deviate a “time Weibull distribution” with the relation of

$$m^* = \frac{m}{n - 2}$$  

The time Weibull modulus m* takes the inert flaw distribution (represented by the strength Weibull modulus m) as well as the SCG susceptibility (represented by the crack growth exponent n) into account [3,10]. Such a relationship further allows the design and presentation of fatigue data in a strength-probability-time (SPT) diagram.

A way to overcome highly scattered data is to observe real crack extensions from artificially produced sharp notched or pre-cracked specimens such as double-torsion specimens. A single defined crack is intentionally prepared to start the slow crack growth and to exclude the probabilistic nature of a natural flaw population. Such a pre-crack is much deeper compared to the common natural flaws and thus determines the onset of crack growth. This type of experiment however is based on the direct observation of crack velocities, which gives rise to glaring drawbacks regarding the experimental procedure (see Table 1).

4. Microstructural considerations

The smallest flaw size in a partially crystalline material is the single microstructural unit, e.g., grain or crystalite sizes [25,26]. Smaller microstructural units (grain size reduction) would account for a narrow flaw distribution and thus a low scattering of the data, but in contrast they would limit the crack resistance of a material. The fracture toughness of a ceramic is determined by the size of the microstructural unit and in consequence will determine the slow crack growth resistance (see Fig. 2). Especially in high-crystalline (lithiumsilicates) or polycrystalline ceramics (alumina and zirconia), in which cracks are forced to deflect around crystallites or grains, cyclic degradation of strength occurs as result of friction between opposing walls of a crack arising from the rough fracture planes. For such materials the stress amplitude applied in cyclic loading tests has a stronger influence, since low stress amplitudes induce little crack opening, while high amplitudes result in higher friction and strength degradation [27]. Loose debris, usually from deterioration of crack bridges, can further get wedged between the two crack surfaces and also contribute to degradation [28]. An overview of relevant toughening mechanisms in brittle ceramics is shown in Fig. 4.

Fatigue crack extension is generally driven by intrinsic versus extrinsic microstructural toughening mechanisms. While intrinsic mechanisms are determined by the microstructure ahead of an advancing crack, the latter acts in the wake behind the crack tip. Ritchie provides a profound insight into competitive toughening mechanisms relevant for brittle ceramics [28].

Fig. 5 shows an example of crack deflection and zone shielding toughening mechanisms in a lithium disilicate glass-ceramic. Elongated Li2Si2O5 crystals account for an effective crack deflection and twisting of a crack front, thereby substantially dissipating fracture energy. Lithium disilicate exhibits a fracture toughness from 2MPa m0.5 up to 3.5 MPa m0.5 [29,30].

Fatigue experiments using uncracked specimens (natural flaw distribution) are generally understood as “accelerated testing” that use loads much higher than those seen clinically to create realistic testing times. As long as the failure mechanisms (origin, flaw type, damage) under accelerated conditions are similar to those reported for clinical service failures, accelerated tests are valid. Cycling frequencies can also be accelerated above clinical values (approx. 0.5–1 Hz). When fatigue effects primarily involve chemically-assisted
crack growth, cycling frequency or waveform generally have no effect on lifetimes [13].

When damage accumulation involves nucleation of volume defects (e.g., intergranular microcracking) higher cycling frequencies can be more damaging. There can also be beneficial effects of cyclic versus static loading where damage accumulation involves microcrack deflection or crack wake bridging and conceivably also in the case of incremental toughness increases with tetragonal to monoclinic transformation. Such materials are considered “damage tolerant” [13].

5. General approaches to fatigue testing

Sensitivity to damage accumulation can be tested as a material parameter (e.g., static fatigue), as a material/environment response (e.g. strength decrease following cyclic loading) and additionally as a ceramics design issue, i.e., developing robust designs to minimize fatigue strength degradation. Both the design (influencing stress concentrations, development of compressive versus tensile stresses during service) and the processing of the ceramic (involving every stage in the fabrication process from powder formation, powder packing, sintering, to machining and finishing) have a profound influence on the stress distribution during service and the inherent flaw distributions.

It has to be mentioned that in a variety of materials mechanical fatigue is counteracted by an increasing resistance to crack growth (R-curve effect) [10]. The R-curve effect is typically found in polycrystalline ceramics (e.g., zirconia) or high vol% crystallized glass-ceramics and has an overarching effect on fatigue degradation. Toughening mechanisms responsible for the R-curve [28] also get degraded and account for the fatigue in these materials. The R-curve is not part of this guidance document and further reading is referenced [19,20].

A wide variety of approaches to fatigue testing has been developed for ceramics, some originating from the community of engineering ceramics and some originating within dentistry especially in relation to the testing of whole prostheses or their components:

- Standardized fatigue testing.
- Slow crack growth experiments on in vitro specimen.
  - Static method.
  - Dynamic method.
  - Cyclic method.

- SFT diagrams (stress-probability-time) coupling crack growth exponents with Weibull statistical analysis of static failure probabilities so as to extrapolate failure probabilities to clinical lifetimes (also in correlation with clinical data).
- Threshold concepts.
- Clinically relevant structural testing.
- Fatigue testing of non-clinical specimens under conditions reproducing clinical failure.
- Fatigue testing of realistic prostheses to failure.
- Strength degradation under cyclic loading and “fatigue challenge” to prostheses (“aging”) prior to static testing.

6. Slow crack growth parameters

It has already been shown in the late 1950s that brittle solids such as glasses or ceramics tend to degrade mechanically under external loading [5]. Either water vapor or a humid environment can significantly accelerate the chemical corrosion process directly at the crack tip of a critical material defect. This occurs preferentially in silicate base glasses, which are present in many dental ceramics, and results in bond rupture. Even moisture levels as low as 0.02% relative humidity are known to cause stress corrosion [19,31].

Based on the Griffith failure criterion [1] for brittle ceramics (K1 > Kc) the crack growth rate da/dt can be expressed as a power function of the applied stress intensity K as shown in Eq. (1). The subcritical crack growth parameters n and A characterize the growth rate of flaws in ceramics [10,32,33]. These parameters are commonly applied in either direct or indirect measurements under static, dynamic or cyclic loading conditions, as summarized in Table 1 and shown in Fig. 6 for indirect measurement techniques.
Fig. 6 – The three types of loading commonly used for fatigue experiments and determination of slow crack growth parameters $n$ and $\Delta$: (a) static loading: a constant fatigue load is sustained until fracture. (b) Dynamic loading: the load is increased by a fixed rate until fracture. (c) Cyclic loading: loading and unloading take place at a fixed frequency and load amplitude ($R$-value).

7. Static method

The static method is a test with constant stress over time [15,34]. The experiment determines the time-to-failure of a specimen or structural component. In principle, a series of experiments at decreasing constant loadings would exhibit increasing static lifetimes of the material under investigation. The calculated static lifetimes show a strong dependency on the applied stress level, especially for highly glassy silicate based ceramics with a low crack growth exponent $n$ [10]. The threshold value $K_{0}$ (below which no crack growth is expected) for slow crack growth can be adequately approximated using the static fatigue method. Modifications such as the interrupted static fatigue test have also been proposed for $K_{0}$ determination [34,35]. This approach however suffers from great data variability.

8. Dynamic method

This method uses different constant stress rates during flexural strength testing to determine subcritical crack growth parameters [36–38]. Stress rates are generally widely separated over orders of magnitude, i.e., 0.1, 1.0, 10 and 100 MPa/s. The graphical solution of a typical dynamic experiment and considerations on the applied evaluation procedure are shown in Fig. 7. One could possibly infer from Fig. 7b that the reliability of a $n$-value prediction is maximized by using Weibull scale parameters for the approximation as they keep the $n$-value deviation to a minimum [39]. In one analytical method, the slopes of ln(fracture stress) versus ln(stressing rate) are used to determine crack growth parameters. Good examples of this protocol can be found in basic research on dynamic fatigue [32]. Relevant standards for the dynamic method are ASTM C 1368 and EN 843-3 [16,17]. Another method plots the log(fracture stress) versus log(average time to failure) for each stress rate [33]. In an alternative to this, discs were cyclically stressed at 4 Hz in biaxial flexure to three maximum stress levels. The slope of the log(maximum stress) to log(time to failure) plot was used to calculate crack growth parameters [40].

9. Cyclic method

The most clinically relevant fatigue approach however is the cyclic method. Despite the fact that these experiments are by far the most time consuming, they produce the best insight in the material response for a complete service life. The most comprehensive approach is the determination of stress-cycles-to-failure plots (S–N, Wöhler curve). The principles and the loading variables are shown in Fig. 8.

A schematic of typical S–N (Wöhler) curves for different cyclic fatigue degradation patterns is shown in Fig. 9. Both curves show a considerable degradation at high stress amplitudes. The material is intended to fail with a low number of cycles (LCF, low-cycle-fatigue) whereas at low

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stress amplitudes materials show a fatigue limit (curve A), commonly reached beyond $10^5$–$10^6$ loading cycles (HCF, high-cycle-fatigue). Fatigue or endurance limits imply that there is a stress below which failure will not occur under an assumed upper limit of cycles. S–N curves use specimens for which analytical stress solutions exist such as 3-point and 4-point bend bars or biaxial flexure discs. Data is plotted as stress versus log(cycles). Fracture surface analysis is recommended for all specimens to ensure that failure occurred from the location assumed in the analytical stress solution. One very good example of such testing of Y-TZP zirconia in water is seen in [41]. The application of fractography on fractured specimens is described in another ADM guidance document (www.academydentalmaterials.org) [23].

Fig. 8 – Loading regime in a typical cyclic experiment simulating oral mastication, outlined by the mean stress $\sigma_m=\left(\sigma_{min} - \sigma_{max}\right)/2$, the stress amplitude $\sigma_a=\left(\sigma_{min} + \sigma_{max}\right)/2$, and the stress ratio R. The stress ratio between a lower and upper stress (R-value $= \sigma_{min}/\sigma_{max}$) at a certain mean stress $\sigma_m$ defines the experimental loading conditions, e.g., the compressive repeated loading with $\sigma_{max}$ and $\sigma_{min}$ being compressive ($-1 < R < \infty$). A special type would be a complete unloading between cycles ($\sigma_{max} = 0$, $\sigma_m = \sigma_a$, and $R = 0$).

Fig. 9 – schematic S–N-graphs showing the strength degradation (S) for two materials with increasing load cycles (N). In general, different material behavior accounts for either a fatigue (or endurance) limit (curve A) or an ongoing degradation at low stress amplitudes (curve B).

More efficient approaches (in terms of time and effort) are based on statistical procedures such as the staircase, stepstress, or boundary approaches (see Table 1). The drawback of those methods is mostly related to the limitation they impose on any phenomenological insight as to the material’s behavior. Those methods provide a limited picture of the more complete S–N curve. Slow crack growth parameters (n and A) cannot be estimated using those methods.

10. SPT diagrams (strength-probability-time)

The main goal of the use of the techniques described above however is to approximate and design the lifetime of a ceramic component. For this reason, knowledge of the relationship between strength and time is mandatory (determination of slow crack growth parameters n and A). The combination of a material’s fatigue behavior and its statistical treatment of fracture strength (namely Weibull distribution) allows for an extrapolation of lifetimes. The relationship between (fracture) Strength, (failure) Probability and (life) Time can be illustrated for a ceramic material in SPT-diagrams (see Fig. 10).

In more complex work, data from Weibull parameters and dynamic crack growth measurements were combined to plot SPT diagrams to extrapolate for lifetime predictions [37,42]. Weibull distributions were used in examining cyclic flexure as well as cyclic torsion of Y-TZP specimens in air and water [43]. Both loading scenarios exhibited similar crack growth parameters in air and water. However, threshold values $K_{th}$ were
lower and crack growth rates were higher in water, reflecting the influence of stress corrosion at the crack tip. K_{10} for crack propagation in water was significantly lower than the critical K_{c} (~50%) [43]. SPT diagrams were also used to investigate the influence of the microstructure of five different ceramics on their lifetime estimates [36]. A correlation of in vitro measured lifetimes with clinical outcome from prospective long-term studies of course would be an ultimate goal. However, there are several boundary conditions and simplifications regarding the specimen geometry involved in SPT lifetime predictions, restricting the transferability to clinical findings. Estimative approaches are described in the literature with indications for an in vitro/in vivo correlation [44].

11. Threshold concepts

Another important concept on the “other end” of the fatigue phenomenon for ceramics is that for some ceramics there can be a stress intensity below which crack growth does not occur [45,46]. This implies that a threshold intensity factor can exist as a lower boundary for crack propagation. Threshold intensities have been measured for 11 dental ceramics, and they generally are below 1 MPa m^{0.5} to around 2 MPa m^{0.5} for polycrystalline ceramics [45]. It is interesting that the threshold for alumina and zirconia are nearly identical.

In another method the crack growth rate was observed arising from advancing edge cracks created by Vickers indentations [46]. This represents an inverse approach since cracks are formed from the surface to the respective crack tips.

A study on 3Y-TZP employing the double-torsion method has compared crack growth velocities under static and cyclic loading conditions and has found a higher susceptibility to slow crack growth under constant loading conditions. On the other hand, this study has also shown a decrease in threshold value K_{th} due to repetitive cyclic loading [27].

In general, due to the inability of most fatigue machines to “handle” zero load, testing is done from 10 N or 20 N to the target load or from 10% to 100% of the target load. Ceramics are generally tested in water due to their sensitivity to chemically-assisted, or slow crack growth. The starting load for fatigue testing is often 30–60% of the mean monotonic failure loads.

12. Fatigue testing of non-clinical specimens under conditions reproducing clinical failure

The key to doing this in a meaningful fashion is to create the same crack system as seen in bulk clinical failure. This means creating the same stress system and driving failure from flaw types encountered in clinical specimens. This type of test involves cyclic loading of cemented discs-tabs or flat crowns, either monolithic or bilayered, with a blunt piston simulating loading at wear facets [47]. This setup invokes failure due to radial crack formation from the intaglio surface, which has been identified as the fracture origin site in a study by Kelly et al. [48] and Thompson et al. [49] on clinically-failed crowns. Cracks are usually detected by translumination following a certain number of cycles and the up-down or staircase method of statistical design is used to obtain means and standard deviations [50]. Loads are usually compared, since good analytical solutions do not exist for blunt loading where the piston radius exceeds the ceramic thickness [51]. It is therefore critical that all specimens are of the same thickness. Stresses can be calculated using numerical solutions. While crowns having normal anatomy could be tested, this becomes experimentally cumbersome and is really not needed since the stress on the intaglio surface would simply be a trigonometric ratio of the load applied to a flat surface.

Another type of mechanical fatigue, highly relevant in dentistry, is contact fatigue, resulting from repetitive contact between two bodies (tooth–tooth, tooth-restoration or restoration–restoration). Contact between teeth/restorations take place on round and flat surfaces of the occlusal surface (cusp–cusp, cusp-incline or incline–incline), resulting in local stress concentrations following the fundamentals of contact mechanics. The contact between a round indenter and a flat surface usually generates a crack type called a cone crack, which begins as a ring crack on the surface and extend towards the interior of the material at an angle, forming a cone geometry [52]. Cone cracks form around the contact area, where tensile stresses are formed. The initiation of ring cracks and growth of cone cracks depend mainly on the elastic modulus and fracture toughness of the contacting material, such that the lower these properties, the lower the necessary load for crack formation [53]. Because jaw movement occurs during mastication, friction develops at the contact area, increasing the local stress concentration. A new type of crack is formed due to sliding, partial cone cracks, forming a trail behind the moving indenter [53].

13. Fatigue testing of realistic prostheses to failure

In addition to in situ testing of single-unit crowns, research on multi-unit prostheses is often a challenge, with failure most frequently occurring from cracks originating from the gingival side of connectors [49,54]. Many aspects of the connector design control failure loads, including connector height (squared), connector width (linear), connector radius and whether the connector is veneered [43,55]. Since “strength” of the connector is dependent upon the height squared and is linear with width, connector area is not a good criterion to predict fatigue behavior of dental prostheses [56,57]. Stresses are concentrated in connectors due to the very slight tipping of abutment teeth, so some method of replicating this is needed, e.g., an artificial periodontal ligament made of poly(vinyl siloxane) [58,59]. Considering all the above, it is important to fabricate connectors that are as identical as possible within the entire experiment. Once again, failure loads are generally used for statistical comparisons. The empirically determined starting load for fatigue testing is often between 30% and 60% of the mean monotonic failure load. A very helpful tool for this type of experiment is to use CAD/CAM to produce prostheses, since design and dimensions can be kept constant for a population of test specimens.

This type of simulated “proof-testing” aims to investigate the clinical service life of an individual restoration made of a certain ceramic material [10]. Beyond an extensive data
basis for the materials tested, the underlying fracture mechanics principles remain the same and found application in the analysis of the individual components. Essential tools for predicting the performance of complicated structures are numerical simulations. Those methods allow for optimization of design and function and might extend their value to fracture statistics as well as for lifetime predictions. Valuable information on imperfect processing, improper use, or design issues can be further identified by a close fractographic examination of the fractured fragments. A separate ADM guidance document presents fractographic techniques and application (www.academydentalmaterials.org) [23].

14. Strength degradation under cyclic loading

There is an unfortunate trend towards “aging” prostheses and specimens prior to static testing. For example specimens may be loaded to 50N for one million cycles, and perhaps even thermal cycled, before single load-to-failure testing. The assumption is that some “realistic” damage accumulation is occurring. This assumption of damage accumulation is commonly approached in chewing simulation studies. Chewing simulators are typically used to simulate the clinically masticatory process and to produce relevant long-term cyclic fatigue resistance data from non-clinical specimens. However, the experimental settings in such an approach need to be carefully adjusted in order at least to create some damage accumulation [60,61]. If not, the investigators are wasting their time and then misleading readers as well. Hence, if one wants to measure strength degradation, the testing conditions should not be arbitrarily chosen but determined a priori in a pilot study. Additionally, “aging” conditions should not be so severe as to be clinically unrealistic. Further insight into different chewing simulation approaches, techniques and individual machines as well as recommendations towards reliable pre-clinical testing of individual prostheses are summarized in a separate ADM guidance document (www.academydentalmaterials.org) [62].

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