R-Curve Behavior of Monolithic Ceramics

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Extended Abstract

The inherent brittleness of ceramics provides a severe mechanical disadvantage which largely limits a broader use of these materials in advanced structural components. Furthermore, often the poor reliability due to the scatter in fracture stresses does not facilitate applications. About two decades ago, it was first observed that certain technical ceramics are able to develop a kind of flaw tolerance by an increase of toughness with crack extension. Since then this favorable crack resistance (R-curve) behavior has gained considerable interest in the ceramic community. The involved toughening mechanisms have been studied and the recognized principles of energy dissipation and crack tip shielding /1-3/ are increasingly utilized to tailor ceramics and ceramic composites with reduced brittleness.

The review focuses on R-curve behavior of monolithic ceramics. Key experimental results and the underlying toughening mechanisms are presented. The impact of R-curve behavior on fatigue and reliability is addressed.

Examples of monolithic ceramics with pronounced R-curve behavior (coarse grained Al_2O_3 /3/ and Si_3N_4 /4/, thermal shock resistant magnesia partially stabilized zirconia (Mg-PSZ /3/)) are shown in Fig. 1. The R-curves represent toughness data derived from stable crack propagation experiments with long cracks in fracture mechanics specimens. For the selected ceramics the increasing toughness approaches a plateau value after a certain amount of crack extension. In many other variants of monolithic ceramics the rising part of a R-curve is often so steep that it is not recognized in the long crack experiments.

In non-transforming ceramics like Al_2O_3 and Si_3N_4 the toughness increase depends on microstructural properties such as grain size and grain morphology, but also the grain boundary phases are of importance. R-curves are usually well pronounced in the case of intergranular fracture of coarse grained materials or in materials with elongated grains. However, not only material related properties like the mode of micro-fracture, but also the chosen testing geometry influence the shape of the R-curves. The effect of the testing geometry becomes especially significant for long cracks which are comparable in size to the specimen geometry.

Moreover, the toughness as derived from the plateau value of pronounced long crack R-curves is not really suitable for a failure relevant fracture characterization of monolithic ceramics. Since in such cases the plateau toughness is only reached after a crack extension considerably larger than in a real failure situation, a non-conservative estimate is given. From the fracture mechanics point of view only R-curve behavior of short cracks, i.e. of the failure causing flaws, is of relevance. To date only few R-curves of short cracks have been determined from in situ observation of the growth behavior of natural flaws. Fig. 2 shows two examples, the short crack R-curves of a coarse grained Al_2O_3 and Mg-PSZ. Both ceramics exhibit a fairly large regime of stable crack growth. In comparison to the long crack data of both materials (Fig. 1) the measurable crack extension is limited because the specimens fracture due to crack instability. Most interestingly, both curves start at a lower toughness than their long crack counterparts. Clearly such short crack R-curve data are required to characterize the failure relevant fracture behavior of "flaw tolerant" monolithic ceramics.

The mechanisms which govern the R-curve behavior have been analyzed from crack growth studies with long cracks. The studies revealed that R-curve behavior of monolithic ceramics is unambigously related with wake controlled crack tip shielding. In zirconia containing ceramics a transformation zone of compressive stresses develops along the crack surfaces in the wake of a propagating crack. The wake stresses counteract to the applied crack opening forces. The more the crack grows the more the crack tip is shielded. The effect saturates at larger crack extension. A similar but weaker zone shielding occurs in ceramics which dissipate energy by stress induced micro-cracking. In non-transforming ceramics a wake controlled shielding with physical crack surface contact is dominant. This crack bridging effect also saturates when the crack opening displacement exceeds the size of the bridging ligaments (~ grain size). The bridging mechanisms could be convincingly demonstrated with alumina by cutting away the serrated grains in the wake regime of a long crack. Accordingly, the toughness decreased again to the crack tip value. More sophisticated experiments, e.g. by preparation of tensile specimens from the wake region /5/, allowed to measure the stress separation behavior of the bridging elements experimentally. Alternatively, also the contour of the crack profile, which reflects the influence of the bridging elements, can be measured to derive, based on weight function approaches, the separation function /6/. Typically a friction related separation mechanism dominates.

The separation behavior of the bridging elements is characteristic for a given ceramic material and defines the R-curve effect in the case of contact shielding. With the characteristic separation function of a bridging element the R-curve can be modeled for each crack and specimen geometry. The toughness enhancement by incorporation of wake controlled shielding mechanisms has proven to be successful not only in monolithic ceramics. Note that the development of second phase reinforced ceramic composites ,e.g. by whisker, fibers and particles, follows a similar concept.

Although monolithic ceramics with R-curve behavior lead to an obvious improvement of toughness and an enhanced resistance to static fatigue, they are especially sensitive to cyclic fatigue. For example in the case of contact toughening a repeated opening and closure of the crack reduces the crack tip shielding; the bridging elements are mechanically disintegrated. A disadvantage which must be considered when using R-curve toughened monolithic ceramics under such service conditions.

Finally it should be emphasized again that in absence of cyclic stresses a pronounced R-curve behavior improves the reliability of ceramics. If the critical defect size, which determines catastrophic failure of the material, is no longer uniquely related with the initial flaw size but also depends on the further stable flaw extension along the R-curve, a mechanically more reliable ceramic with better predictable failure behavior exists.

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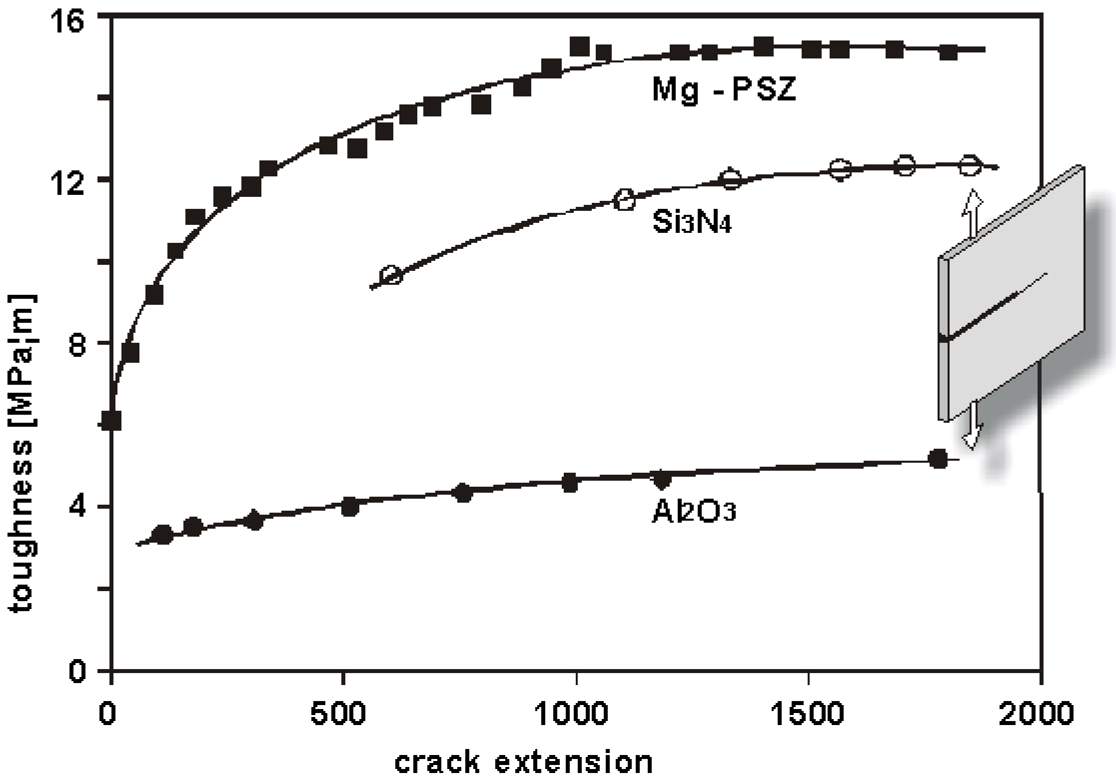

Fig. 1: R-curves of long cracks

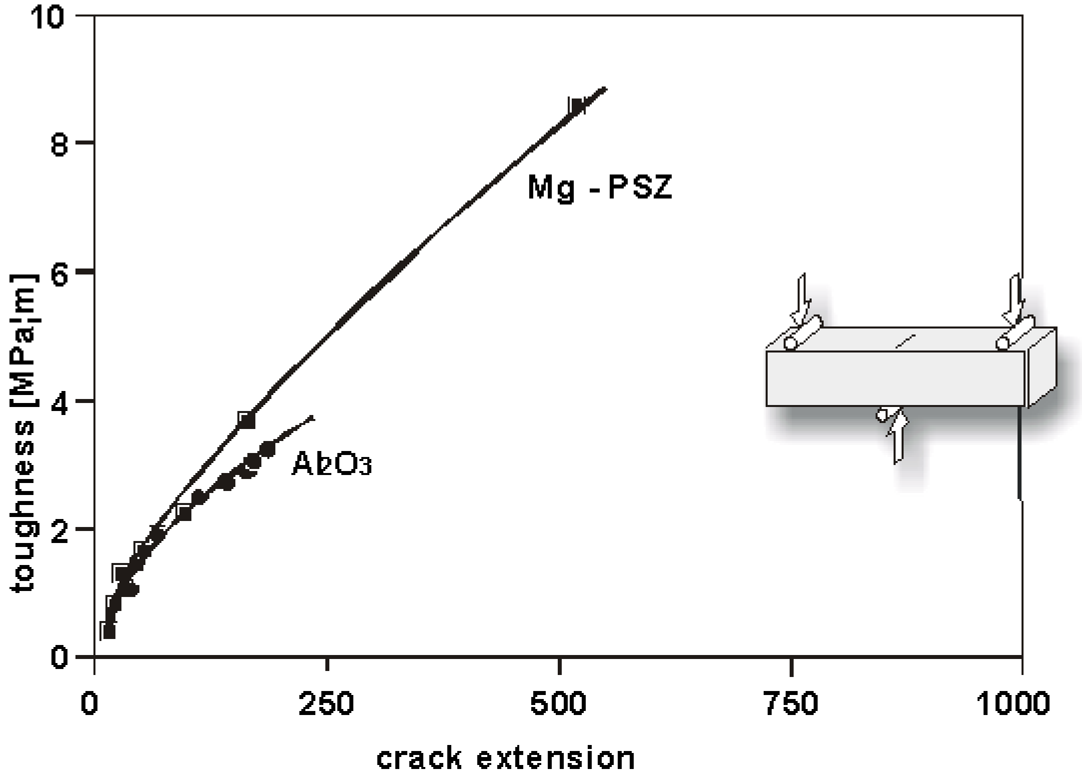

Fig. 2: R-curves of Ñnaturalì flaws

Atti del convegno

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