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Deformational Behaviour of Ceramics

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Abstract

The application of modern ceramics, such as cordierite or partially stabilized zircona (PSZ), calls for more detailed data than those provided by conventional investigation of strength or crack-resistance characteristics. To provide data on deformational behaviour (including possible inelasticity), a parameter is proposed in the form of a 'brittleness measure', χ. At $\chi = 1$, a ceramic obeys Hooke's law and in its mechanical behaviour is similar to glass. At the same time, its behaviour under loading is like that of concrete and it does not correspond to the elastic-solid model.

It has been found that aluminium oxide toughened by zirconium dioxide and zirconium dioxide stabilized by yttrium oxide are characterized by the $\chi = 1$ parameter, while cordierite, silicon nitride with boron nitride, corundum refractory material with zirconium dioxide, and zirconium dioxide stabilized by magnesium oxide are characterized by $\chi < 1$. It is shown that, unlike ceramics with $\chi = 1$, ceramics with $\chi < 1$ retain residual stresses. Being inelastic, they have an ascending R-curve and show insignificant differences in the values of the critical-stress-intensity factor obtained for specimens with a notch and sharp crack. The analytical evaluation of such ceramic materials should be based on the proportionality limits rather than on the ultimate-strength values. Thermal-shock-resistance criteria should take into account the actual values of ultimate strains.

The data presented reveal that, in the evaluation of serviceability, specific features of mechanical behaviour are as important as absolute values of properties. The values of the parameter χ and ultimate strains may be regarded as important physico-mechanical characteristics of this type of material.

Die Anwendung moderner keramischer Werkstoffe wie Cordierit oder teilweise stabilisiertes Zirkonoxid (PSZ) verlangt detailliertere Materialkenngrößen als die übliche Angabe der Festigkeit oder Zähigkeit. Um das Deformationsverhalten (einschließlich einem möglichen nichtelastischen Verhalten) besser beschreiben zu können, wird ein neuer Kennwert, die 'Sprödigkeitszahl' χ vorgeschlagen. Ein keramischer Werkstoff mit $\chi = 1$ folgt dem Hookeschen Gesetz und verhält sich mechanisch ähnlich wie Glas. Zugleich entspricht sein Verhalten unter Belastung dem von Beton und gehorcht nicht dem Modell des elastischen Festkörpers. Die experimentellen Ergebnisse zeigen, daß für ZrO_2 verstärktes Al_2O_3 und Y_2O_3 stabilisiertes ZrO_2 $\chi = 1$ ist, während Cordierit, Si_3N_4 mit BN, Korund-Feuerfestmaterial mit ZrO_2 und MgO stabilisiertes ZrO_2 durch einen χ-Wert < 1 gekennzeichnet sind. Es hat sich gezeigt, daß, im Gegensatz zu Keramik mit $\chi = 1$, in Materialien mit $\chi < 1$ Eigenspannungen zurückbleiben. Da sie nicht elastisch sind, zeigen sie eine ansteigende R-Kurve, und zwischen K_{Ic}-Werten die aus Proben mit einer Nut und einem scharfen Anriß bestimmt wurden, besteht nur ein unwesentlicher Unterschied. Die experimentelle Beurteilung solcher keramischen Werkstoffe sollte sich mehr auf die Proportionalitätsgrenzen stützen als auf die absolute Bruchfestigkeit. Thermoschockkennwerte sollten die tatsächlichen Bruchdehnungen einbeziehen. Die gefundenen Daten zeigen, daß bei der Beurteilung der Einsatzfähigkeit keramischer Werkstoffe spezielle Aspekte des mechanischen Verhaltens genauso wichtig wie Absolutwerte einzelner Eigenschaften sind. Die χ-Werte und die Bruchdehnungen dieser Werkstoffe sollten als wichtige physikalisch-mechanische Größe mitberücksichtigt werden.

L'emploi de céramiques modernes telles que la cordiérite ou la zircone partiellement stabilisée (PSZ)

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requiert la connaissance de données plus détaillées que celles fournies par les essais classiques de résistance mécanique ou de ténacité. On propose un paramètre sous forme de 'mesure de fragilité', χ, destiné à fournir des valeurs se rapportant au comportement en déformation (incluant une possible inélasticité). Pour $\chi = 1$, une céramique obéit à la loi de Hooke et son comportement mécanique est similaire à celui des verres. D'autre part, sous comportement sous charge est semblable à celui du béton et ne correspond pas au modèle du solide élastique. On a établi que l'oxyde d'aluminium renforcé par le dioxyde de zirconium ainsi que le dioxyde de zirconium stabilisé par l'oxyde d'yttrium sont caractérisés par $\chi = 1$ alors que la cordiérite, le nitrure de silicium avec du nitrure de bore, le réfractaire corindon avec du dioxyde de zirconium et le dioxyde de zirconium stabilisé à l'oxyde de magnésium possèdent un $\chi < 1$. On montre qu'à la différence des céramiques présentant $\chi = 1$, celles ayant $\chi < 1$ retient les contraintes résiduelles. Etant inélastique, il montre une courbe R ascendante et la différence entre les valeurs du facteur critique d'intensité de contrainte mesurées sur des éprouvettes fissurées par indent ou par entaille est minime. L'analyse de ce type de matériaux céramiques doit plutôt être basé sur les limites de proportionnalité que sur les valeurs de résistance finale. Les critères de résistance au choc thermique doivent prendre en compte les valeurs actuelles de déformations finales. Les données présentées ici montre que les caractéristiques spécifiques du comportement mecanique sont aussi importantes que les valeurs absolues des propriétés lors de l'évaluation du comportement en service. Les valeurs du paramètre 'χ' et les déformations finales atteintes doivent être considérées comme des caractéristiques physico-chimiques importantes pour ce type de matériau.

Introduction

The selection of structural ceramics for specific applications was originally primarily based on their strength characteristics; their crack-resistance data later began to be taken into account, but attention is still very seldom given to their deformational capabilities. As a result (being aware or unaware of this), they are considered to be linearly elastic and to obey Hooke's law, i.e. to some extent, they are similar to glass, although, in specific features of their mechanical behaviour, these materials, for instance, a zirconia-based one, happen to be in many respects similar to metals and are sometimes, not without reason, called 'synthetic steel'.

A combined physical and mechanical investigation of different ceramic materials has therefore been performed which revealed that the deformation-behaviour parameter (the 'brittleness measure', χ) and the ultimate-strain value should also be referred to as the most important characteristics of ceramics.

Brittleness Measure

On the basis of the data of investigations of ceramics and similar materials, the author[1] demonstrated that they should be classified into those linearly deforming right up to fracture (called 'brittle ceramics') and those non-linearly deforming after reaching the elastic limit ('relatively brittle ceramics' in contrast to plastic metals). For this purpose, the parameter 'brittleness measure', χ is proposed[2] and is equal to the ratio of the specific elastic energy EE (Fig. 1) accumulated in the ceramics by the moment of fracture to the total specific energy TE spent in its deformation. It represents an energy characterizing the deviation of the actual deformation features of ceramics from those described by Hooke's law.

When the parameter χ is defined in four-point bending of a rectangular-beam specimen, which is generally used to determine ultimate strengths, static elasticity moduli, and other characteristics, it is equal to

$$\chi = \sigma_u^2/2E \, . \int_0^{\varepsilon_u} \sigma \, d\varepsilon$$

where σ_u is the ultimate strength, E is the elasticity modulus, ε_u is the ultimate strain, and σ are the stresses at the current strain values ε. If the ceramics parameter χ is equal to unity, then in its mechanical

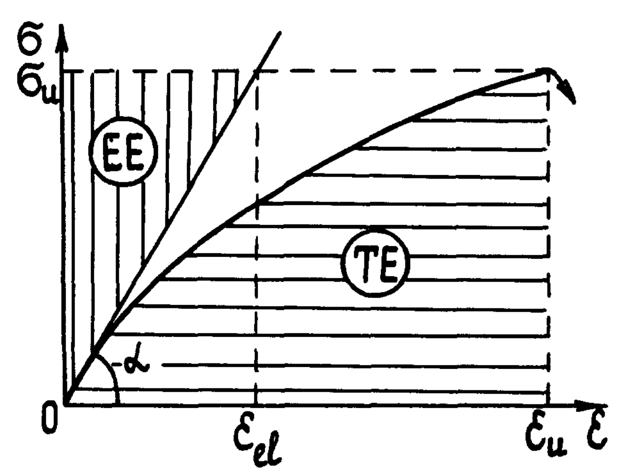

Fig. 1. Ceramic stress–strain diagram: σ_u—fracture stress; ε_{el}—elastic ultimate strain; ε_u—actual ultimate strain; EE and TE—elastic and total fracture energies, respectively.

behaviour the ceramic resembles glass but, if $\chi < 1$, it resembles concrete.

Methods and Materials

The stress–strain relations at ambient and high temperatures were obtained from the data of the load–deflection curves in four-point bending. The internal and external spans were 20 and 40 mm, respectively. Specimens 3·5 × 5 × 50 mm in size were ground longitudinally with the edges rounded. Crack resistance was evaluated on the same specimens in three-point bending, the distance between the load-application points being 20 mm. In this case, in contrast to the preceding test, the specimen was placed on the support rollers with a side of 3·5 mm.

The critical-stress-intensity factors were calculated by the well-known recommended practice of Brown and Srawley.[3] All the experiments were conducted with the aid of devices designed for the purpose and installed on conventional testing machines.

Special attention was given to the device for determining load–deflection curves at ambient temperature, where the usual measurement errors are reduced to the minimum possible.[4,5] The device provides free movement of surfaces of the specimen along its axis during the loading, symmetry of the force-application points with respect to the loading axis, and uniformity of the bending moment in the pure-bending zone and eliminates uncontrollable torques (see the loading-device scheme in Fig. 2). The deflection was measured by a special precision

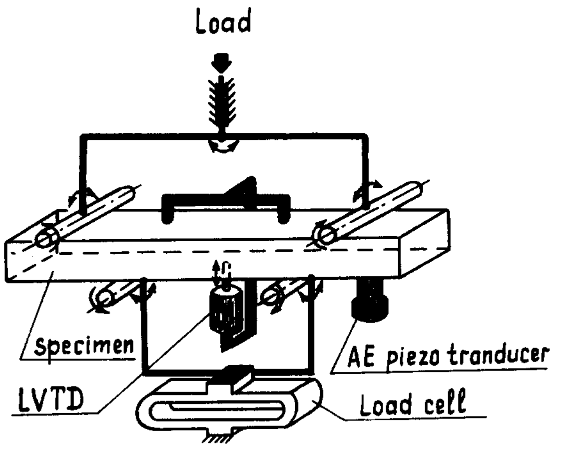

Fig. 2. A schematic diagram of the loading device.

LVDT with a resolution of approximately 0·1 μm suspended from the specimen. To analyse acoustic-emission (AE) signals a semi-conductor transducer was retained against the specimen.

The ceramics studied (see Table 1) were pressed and then burnt with the exception of single crystals, which were made by a skull-melting method. The ZTA ceramics were produced at the Central Institute of Physics of Solids and Materials Science (GDR), the Mg–PSZ in NILCRA (Australia), and the rest in the USSR.

Results and Discussion

When testing the ZTA ceramics (Fig. 3 and Table 1), single crystals of partially stabilized Y–PSZ and Y–PSZ ceramics, they displayed linearly elastic deformation behaviour ($\chi = 1$). The same behaviour was observed for dense ceramics (of less than 15–20%

Table 1. Properties of ceramics

*Ceramic**	*Density, ρ (g/cm^3)*	*Brittleness measure, χ*	*Ultrasonic velocity, V (km/s)*	*Ultimate strength, σ_u (MPa)*	*Ultimate strain, ε_u (%)*	*Elastic modulus (static), E (GPa)*	*Critical-stress-intensity factor, K_{1c} (MPa·m$^{1/2}$)*
ZTA	3·70	1·0	9·35	314	0·097	336	3·5
Y–PSZ	5·81	1·0	6·06	740	0·38	204	10·2
Y–PSZ single crystal	6·35	1·0	5·60	473	0·24	208	7·4
Mg–Al–PSZ	4·82	0·72	5·65	170	0·16	134	3·0
Sialon + 30% BN	2·62	0·70	7·60	160	0·16	137	3·8
Cordierite	2·26	0·60	5·70	40	0·096	76	1·93
Mg-PSZ	5·71	0·41	6·06	506	0·46	204	10·0
$Al_2O_3 + ZrO_2$ (refractory)	3·46	0·36	6·08	23	0·72	88	1·17

* ZTA: Al_2O_3 + 16 mol% ZrO_2
Y–PSZ: ZrO_2 + 6 mol% Y_2O_3
Y–PSZ (single crystal): ZrO_2 + 6 mol% Y_2O_3
Mg–Al–PSZ: ZrO_2 + 6 mol% MgO + 2% Al_2O_3
$Al_2O_3 + ZrO_2$ (refractory): Al_2O_3 + 6% ZrO_2.

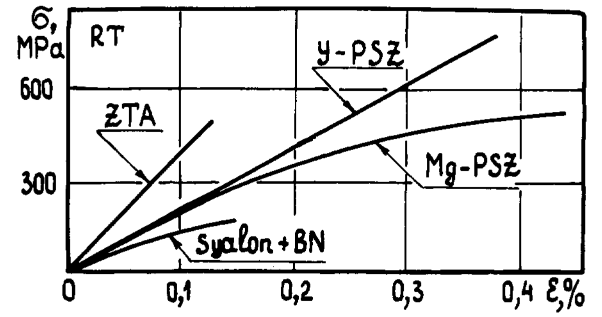

Fig. 3. Stress–strain diagrams in bending (see Table 1).

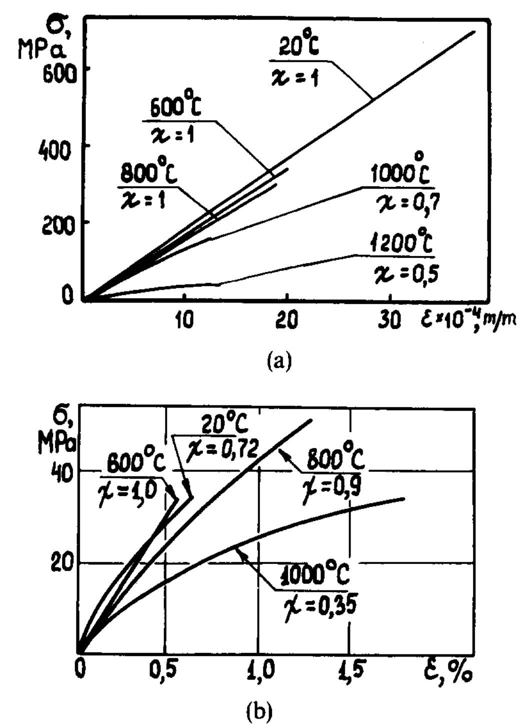

Fig. 5. Stress–strain diagrams of ceramics for different temperatures: (a) Y–PSZ, (b) cordierite.

porosity) based on silicon nitride and carbide, yttria, alumina, and other single-phase or with small addition of fine-grained (grains not less than 10–30 μm in size) ceramics (see ref. 6). Unlike the above materials, multiphase ceramics: cordierite, sialon + 30% BN, refractory ceramics $Al_2O_3 + ZrO_2$,[3,6] as well as magnesium oxide partially stabilized ZrO_2-based ceramics; (for Mg–Al–PSZ and Mg–PSZ, see also refs 7, 8) exhibit nonlinear deformation behaviour ($\chi < 1$). In the latter case, the stress–strain curves also displayed residual deformation at unloading (Fig. 4(a)) and a continuous acoustic emission, which accompanied the specimen loading (Fig. 4(b)).

In heating, the brittle ceramics ($\chi = 1$), similarly to glass at certain temperature levels (generally with softening of the glass phase), display (see Fig. 5) inelastic behaviour.[2,6,8] In contrast with an increase in the test temperature (Fig. 5b) the ceramics with $\chi < 1$ became at first more elastic and then exhibited decreasing inelasticity; this means that there exists a temperature zone where the ceramics, owing to a decline in microdamage, are less sensitive to cyclic and long-term loading. Similar data can be found in refs 2, 8 and 9.

The process of fracture of the ceramics with $\chi = 1$ was substantially different from that of those with $\chi < 1$. Their crack-resistance characteristics turned out to be different as well: for the former, the critical-

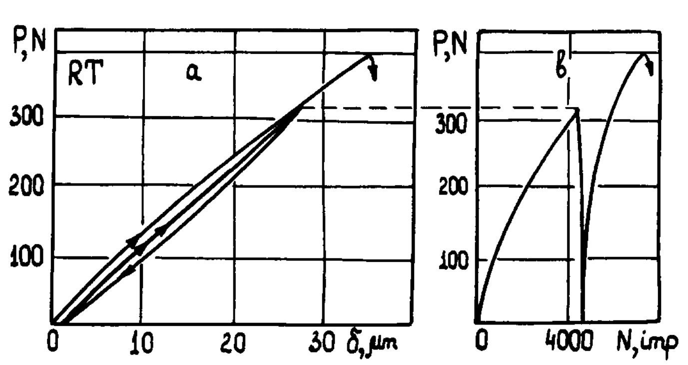

Fig. 4. Cyclic loading of Mg–Al–PSZ ceramics: (a) load–deflection diagram: P = load, δ = specimen deflection; (b) acoustogramme: N–AE total count.

stress-intensity factors K_{Ic}, determined in fast fracture by the conventional method for a notched beam in bending and calculated from measurements of the work of fracture γ_{wof} measured at controlled stable crack growth, were nearly identical.[2,6] For the latter ($\chi < 1$), its fracture energy, calculated in accordance with the Irwin concepts, was less than the work of fracture.[2,6]

Ceramics with $\chi = 1$ are characterized by flat R-curve behaviour. We observed this for glass, hot-pressed silicon nitride and carbide, etc. (similar data are presented in ref. 10). These ceramics demonstrated a 'fracture-barrier effect'[1] (resistance to crack initiation) consisting in the critical-stress-intensity factor values obtained for notched values exceeding those obtained for specimens with a sharp crack.[11] At the same time, for relatively brittle ceramics ($\chi < 1$), this effect was absent,[1] and the R-curve was rising, which is characteristic of cordierite, as well as aluminium titanate and graphite.[10] Those effects are most pronounced for ZrO_2-based ceramics (Fig. 6). If the latter are stabilized by Y_2O_3, then R-curves for both PSZ (sintered and monocrystal) and TZP are flat. For monocrystals, the R-curve slope is independent of the orientation of the monocrystal axes (the monocrystal studied had an elastic modulus of 150–350 GPa and MOR of 400–1250 MPa, respectively). When ZrO_2 is stabilized by MgO, R-curves are rising,[7,8,12,13] as is shown in Fig. 6.

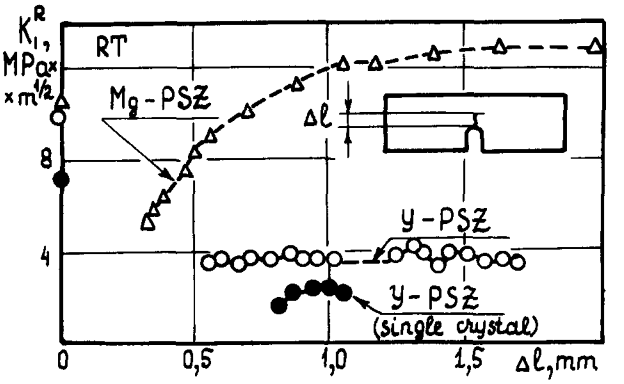

Fig. 6. Ceramics R-curves.

Deformational behaviour of ceramics is important for studying their mechanical behaviour under thermal loading: the greater the ceramic's ultimate strain ε_u (all other conditions being the same), the better is its resistance to thermal deformation. This statement is actually the basis of the first (Kingery) criterion of thermal-shock resistance[14]

$$R' = \sigma_u/E\alpha$$

which involves the ultimate elastic strain ε_{el} calculated in accordance with Hooke's law ($\varepsilon_{el} = \sigma_u/E$) and the linear-thermal-expansion coefficient α. But, if a ceramic is inelastic ($\chi < 1$), then the smaller its brittleness measure χ, the greater is the difference between ε_{el} and the actual ultimate strain ε_u (Fig. 1). If one wishes to consider the known (Hasselmann) energy criterion of thermal-shock resistance,[14] $R^{IV} = \gamma . E/\sigma_u^2$, from the same standpoint as the R' criterion, then the smaller the ceramic's brittleness measure, the larger is the error in the computation of energy (σ_u^2/E) accumulated in the ceramic. The above and some other information made it possible to conclude that the brittleness measure can be used for thermal-shock-resistance evaluation, since the smaller the brittleness measure (under otherwise equal conditions), the better is the ceramic's resistance to thermal loads. It is recommended that the ε_u value instead of the σ_u/E ratio be introduced into the above thermal-shock-resistance criterion.[5]

When measuring ultimate strains in specimens subjected to quenching for determining their residual strength and critical temperature difference,[14] the following findings were made. If the ceramic material is elastic ($\chi = 1$) it is characterized by the critical temperature difference ΔT_c and, after crack initiation, not only the specimen residual strength but also its ultimate strain decreases. If ceramics are characterized by the parameter $\chi < 1$, the value of ΔT_c cannot be generally defined, since, with an increase in the quenching intensity (the difference in the temperature of the furnace and the

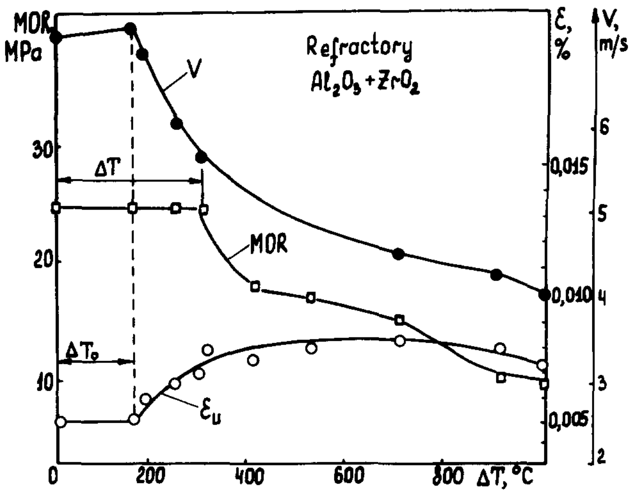

Fig. 7. Thermal-shock-damage diagram: MOR = residual strength; ΔT = quenching temperature in a water bath at ambient temperature; V = ultrasound-propagation velocity in ceramics.

cooling bath), the structural damage increases continuously, and hence the residual strength decreases in subsequent strength tests. One can observe the dependence shown in Fig. 7. For this type of ceramic, the ΔT_0 value is of importance, i.e. the difference in the furnace and quenching-bath temperatures at which its structure begins to fail, the ultrasonic velocity decreases, and deformability increases.[16]

An increase in deformability of relatively brittle ceramics can occur in other cases of the initiation of new or propagation of existing microcracks as was observed for PSZ.[8,9] Thus, for Mg–PSZ (see Table 1), after a 15-min aging at 700°C, the brittleness measure was reduced from 0·44 to 0·31, whereas the residual strains at fracture increased from 0·18% to 0·26%. In other words, the stress–strain diagram of this material changes appreciably.

It should be noted that knowledge of the deformational behaviour of a ceramic is of interest in its strength analysis, since, in choosing the allowable stresses of the ceramic when $\chi < 1$, one should proceed not from its ultimate strength but from its proportionality limit,[1] as is the case in the design of metallic parts.

Conclusions

It has been shown that, for valid estimation of the mechanical behaviour of a ceramic, it is necessary to take into account its deformational behaviour. The magnitudes of its brittleness measure and ultimate strains should be considered as the most important physical–mechanical characteristics of this type of material.

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TS-grade, NILCRA Corp. Australia.

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