SENSITIVITY OF BRITTLE MATERIALS TO LOCAL STRESS CONCENTRATIONS ON THEIR FRACTURE

G. A. Gogotsi[1] **and V. Y. Galenko**

UDC 539.4

Almost the primary source of fracture for the products from brittle materials is known to be local stress concentrations, which results in repeated carrying capacity losses of the material and even of the whole product due to possible crack propagation. For improving the behavior prediction of brittle materials under such conditions, the local stress concentration sensitivity measure is proposed to be introduced (further Measure). This parameter is defined as the ratio of any crack resistance values calculated at low and high stress concentrations. The crack resistance characteristics are known to be usually determined by the techniques based on the concepts and models of linear elastic fracture mechanics aimed at defining the propagation resistance of an already extending main crack or the latter extending from a stress raiser prenotched in testing on the volume specimen fracture. However, other methods do also exist, which make use of parameters that are measured on local specimen fracture in the experiment. The Measure is defined both for volume and local specimen fracture. As large as possible difference in stress concentrations for volume fracture was provided by notching a raiser of the smallest and largest sharpness, which differed by 20–60 times, and for local fracture, it was effected with diamond indenters of the tip radii R varying by about 73 times. The materials with an increased fracture onset resistance barrier were established to also exhibit a higher Measure. Moreover, the Measure determined from the fracture toughness characteristic for volume fracture is much smaller numerically than its value for local fracture near the specimen edge. It is indicative of the prevailing contribution from the mechanisms of the main crack nucleation and initiation resistance in the surface layer of a brittle material to the fracture onset resistance value.

Keywords: crack resistance, brittle materials, indentation chipping, fracture toughness.

Introduction. The application of brittle materials in different fields of modern engineering provokes interest in solving the problem of their catastrophic fracture under the action of local stress concentrations. For improving the behavior prediction for those materials under such conditions, the *local stress concentration sensitivity measure* (further *Measure*) is proposed to be introduced. This parameter is defined as a result of dividing the crack resistance value at low stress concentrations by the value obtained at high stress concentrations. Any crack resistance characteristic seems to be a workable one for determining this ratio. The crack resistance characteristics are known to be usually determined by the methods based on the models of material behavior on their fracture and the concepts of linear elastic fracture mechanics aimed at defining the material resistance to the propagation of an already extending main crack or the latter extending from a stress raiser prenotched in testing on volume specimen fracture. The most commonly used characteristic is the critical stress intensity factor K_{Ic} (MPa $\cdot$ m$^{1/2}$). However, other methods do also exist, based not on the models of material behavior on fracture but only on the parameters measured in the experiment. In this study, one of the methods is the indentation edge chipping of a prismatic specimen. The *Measure*

TABLE 1. Sensitivity of Examined Materials to Local Stress Concentrations

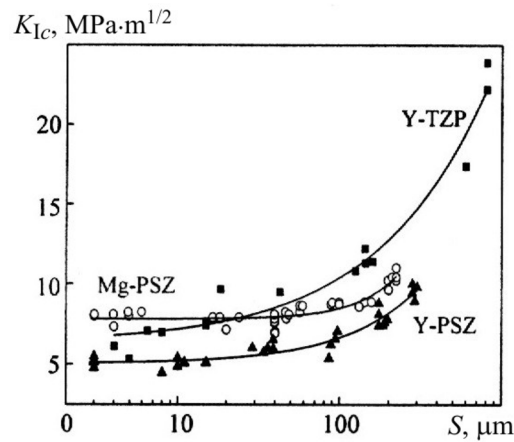| Material	Fracture toughness K_{Ic}, MPa·m$^{1/2}$ Notched specimen bending		Sensitivity measure to local stress concentrations (specimen fracture in bending) $K_{Ic}^{blunt}/K_{Ic}^{GOST}$	Edge toughness E_t, N/mm with an indenter of the tip radius R		Sensitivity measure to local stress concentrations (edge specimen fracture on its indentation) $E_{tR\,800}/E_{tR\,100}$
	Sharp	Blunt		100 μm	800 μm	
Ti$_3$AlC$_2$	–	–	–	262	372	1.42
Mg-PSZ TS	9.12	9.67	1.06	609	1385	2.27
Al$_2$O$_3$	3.00	4.49	1.50	309	827	2.68
Sc$_2$O$_3$	1.57	1.88	1.20	102	311	3.05
Si$_3$N$_4$	4.32	6.77	1.57	360	1162	3.23
Y$_2$O$_3$	3.37	4.64	1.38	238	783	3.29
Y-TZP-A	4.13	5.74	1.39	387	1459	3.77
Glass	0.76	1.35	1.78	118	545	4.62

Fig. 1. Critical stress intensity factor K_{Ic} vs width S of the stress raiser (through transverse notch) in the tensile region of a zirconia specimen tested in bending.

value was evaluated by the crack resistance characteristic for volume fracture (specimen bending with a prenotched stress raiser in the tensile region) as well as by the characteristic for local surface fracture (indentation edge chipping of the specimen).

As large as possible difference in stress concentrations on volume fracture was provided by notching a raiser of the largest and smallest sharpness, which differed by about 20–60 times (Table 1). A further increase in this difference exhibits natural limitations. As is seen in Fig. 1 [1], a decrease in the stress raiser width S, through transverse notch in the tensile region of a specimen tested in bending, does not practically influence the K_{Ic} magnitude, while the width larger than 300 μm (especially in the case of fine-grained materials) effects the crack resistance of the structure rather than the material.

A similar, as large as possible difference of stress concentrations on local surface fracture (specimen edge chipping) with conical diamond indenters of R tip radii reached about 73 times (Table 1). The local stress concentration level under the indenter increases with a decrease of the tip radius R, which leads to the reduction in its contact area with the indented edge surface and growth of specific pressure.

Estimation of the Fracture Toughness K_{Ic} on Volume Fracture of the Specimen. The critical stress intensity factor measurements were performed after a standard SEVNB method [2]. The method provides the stress raiser preforming on the prismatic specimen edge as a through transverse notch of the relative depth $\alpha = a/W = 0.3$–0.5 (notch depth a – specimen thickness W ratio). The notch 200–300 μm wide produced with a diamond disk
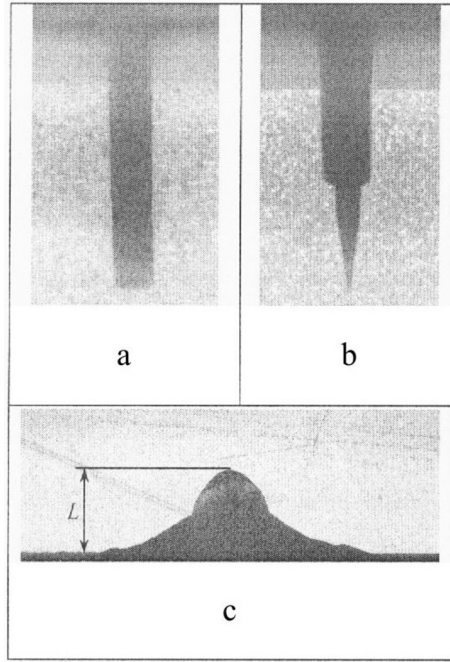
Fig. 2. Profiles of transverse notches for getting low (a) and high (b) stress concentrations and chip (top view) on the indented specimen edge by the EF method (c).

was considered to be "blunt" (Fig. 2a). A "sharp" notch was obtained by deepening a specially prepared shallow blunt notch followed by its sawing with a raiser blade, which was periodically lubricated with diamond paste of decreasing graininess (from 60 to 1 μm). A through V-notch (Fig. 2b) was prepared of an about the same relative depth as the blunt one, but with the width near the base $2\rho = 5$–10 μm. In one disk or blade sawing sharp notches were prepared (as in disk sawing of the blunt one) in five specimens (for statistical processing of test results). The specimens were tested after our SEVNB version [3]. Our version as compared to the standard one [2] featured a decreased span in three-point bending (from 30 to 20 mm). Such small changes, practically without accuracy loss of test results, permitted of essential decrease in the consumption of examined materials. The fracture toughness R_{Ic} [2] was defined as

$$K_{Ic} = \frac{F}{B\sqrt{W}} \frac{L_F}{W} \frac{3\sqrt{\alpha}}{2} Y^*,$$

$$Y^* = \frac{1.99 - \alpha(1-\alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{(1+2\alpha)(1-\alpha)^{3/2}},$$

where F is the fracture force, B is the specimen width, W is the specimen thickness (height), L_F is the distance between the loading points, and $\alpha = a/W$ is the relative depth of the V-notch.

The sensitivity measure to stress concentrations is the ratio of K_{Ic} values determined in testing the specimens with blunt and sharp notches (low and high stress concentrations) ($K_{Ic}^{blunt}/K_{Ic}^{GOST}$ in Table 1).

Fracture Toughness Estimation on Local Fracture of the Specimen Surface. The measurements were performed by the edge chipping method EF [4, 5], where the rectangular edge of a prismatic specimen was chipped with a conical indenter. The force P_{fi} for each chip was determined during the test, then the distance L_i from the specimen edge to the extreme chip scar point was measured with an Olympus BX51M microscope (Fig. 2c). The fracture toughness characteristic, viz the edge toughness E_t (N/mm) was determined from the P_{fi} and L_i values measured for each chip. It is convenient to construct them on the $P_f - L$ plot and approximate by the straight line
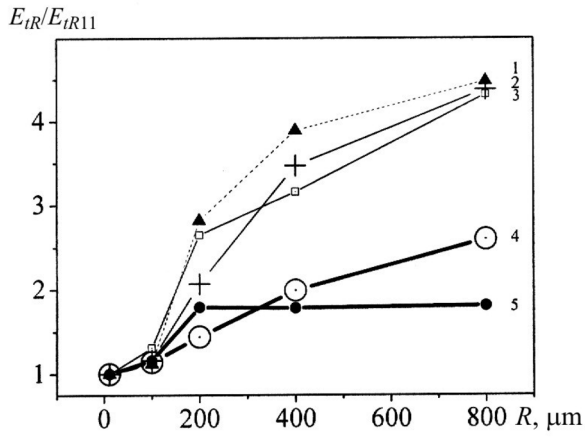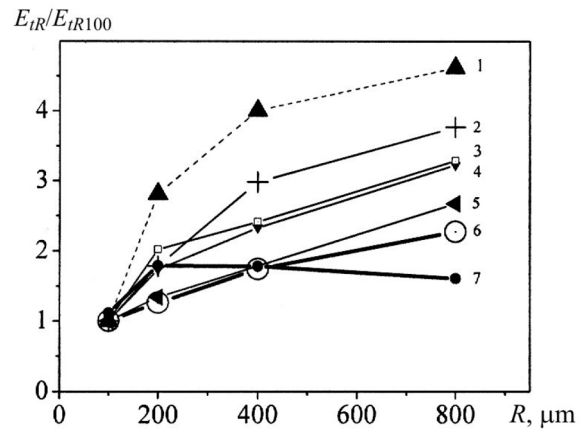
Fig. 3

Fig. 4

Fig. 3. Measure K_{tR}/K_{tR11} vs conical indenter tip radius R for flat glass (*1*), Y-TZP (*2*), Y_2O_3 (*3*), and Mg-PSZ (*4*) ceramics, and nanolaminate Ti_3AlC_2 ceramics (*5*). Line patterns correspond to the materials exhibiting different fracture onset resistance barriers (Fig. 5 [6]): increased – dotted and dash lines, medium (corresponds to the base line) – thin lines, and decreased – thick lines (here and in Fig. 4).

Fig. 4. Measure E_{tR}/E_{tR100} vs conical indenter tip radius R for flat glass (*1*), Y-TZP (*2*), Y_2O_3 (*3*), Si_3N_4 (*4*), Al_2O_3 (Duralbit 90) (*5*), Mg-PSZ TS ceramics (*6*), and nanolaminate Ti_3AlC_2 ceramics (*7*).
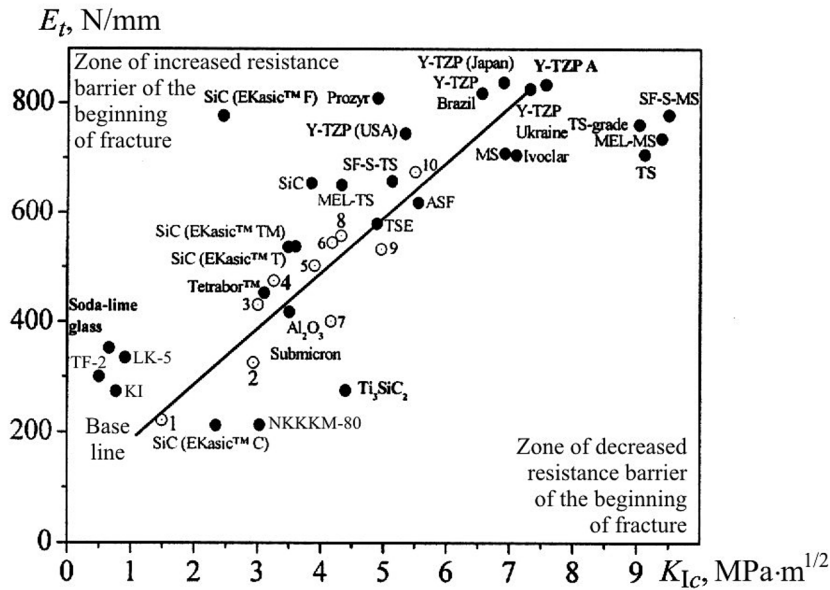

Fig. 5. Classification diagram for glass and ceramics with the base line [6, 7]. The base line is constructed by the points for the ceramics: (*1*) Sc_2O_3, (*2*) Al_2O_3-1, (*3*) Al_2O_3-2, (*4*) Y_2O_3, (*5*) A-999, (*6*) SN, (*7*) HPSN, (*8*) Si_3N_4, (*9*) Y-PSZ, and (*10*) (Y_2O_3, Al_2O_3)-SN.

$P_f(N) = k(N/mm) \cdot L(mm) + c$. The E_t value is numerically equal to the coefficient k in the equation for this line. Such a method of fracture toughness evaluation was also used in [4].

The edge toughness E_t evaluated with diamond indenters of the tip radii $R = 11$, 100, 200, 400, and 800 μm manufactured and calibrated by Gilmore Diamond Tools Inc., USA, was used to calculate *Measure* values.

A maximum difference between stress concentrations is provided with the indenters of the radii $R = 11$ and 800 μm. The *Measure* E_{tR} (for all indenters)$/E_{tR11}$ vs tip radius R is shown in Fig. 3. But the *Measure* value
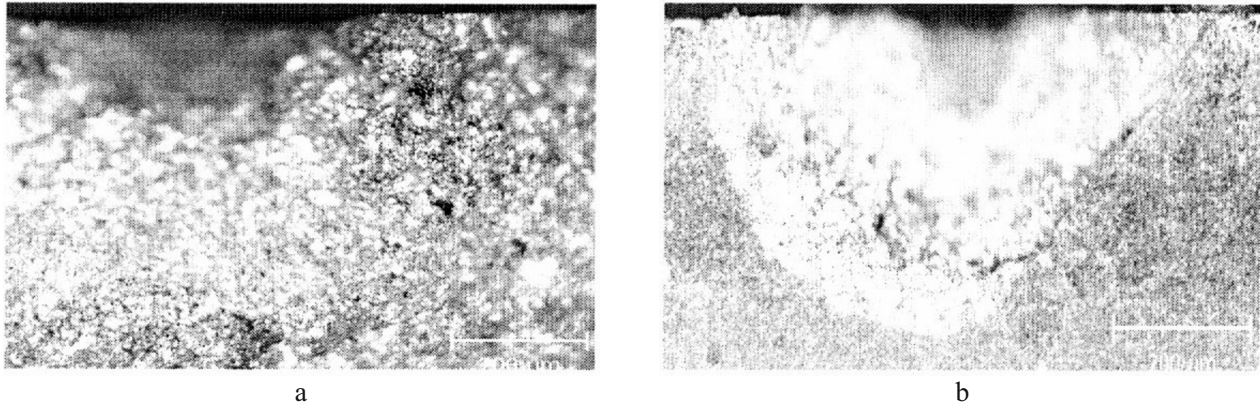
<p style="text-align:center">a   b</p>

Fig. 6. Chip patterns formed on the Ti_3AlC_2 specimen edge effected by the conical indenters of 800 (a) and 100 μm (b) tip radii.

cannot be determined for all materials due to high hardness of several ones (e.g., tool materials), since the risk of breaking the sharp conical indenter with $R = 11$ μm is always run. As is seen in Fig. 4, E_{tR100} determined with a harder indenter of $R = 100$ μm differs from E_{tR11} unessentially. Therefore, the stress concentrations of high level were ensured by the indenter with $R = 100$ μm (Table 1).

Examined materials included both single-phase ceramics, e.g., Al_2O_3 (Duralbit 90) manufactured by Industrie Bitossi S.p.A (Italy) and Y_2O_3, Sc_2O_3, Si_3N_4 (Russia), as well as zirconia Mg PSZ TS ceramics (Nilcra Ceramics, Australia) and Y-TzP-A (ICI Advanced Ceramics, Australia). For comparison, soda glass and nanolaminate titanium aluminous carbide Ti_3AlC_2 were used, the deformation of the latter occurs at the level of nanograins without any apparent signs. For instance, the indentation of its polished specimen surface with a standard Vickers indenter does not result in any cracks from the imprint corners. The test specimens were prepared in the form of prismatic rectangular beams 50 mm long of a 3×4 mm cross-section with polished sides and edge radii that did not exceed 10–15 μm.

Photographs of chips formed on the Ti_3AlC_2 specimen edge effected by the conical indenters of 800 and 100 μm tip radii are shown in Fig. 6.

Conclusions. The characteristic of indirect relation between the ratio of stress raiser sizes providing the lowest stress concentrations in crack initiation regions and the ratio of fracture toughness at the lowest and highest stress concentrations was proposed and termed "sensitivity measure to local stress concentrations." Materials with an increased fracture onset resistance barrier are established to exhibit a higher *Measure* and the *Measure* evaluated by the fracture toughness characteristic for volume fracture, i.e., obtained by the methods based on linear elastic fracture mechanics concepts, is numerically much smaller than that measured by the fracture toughness characteristic for local fracture. It may be the evidence of the dominant contribution from the main crack nucleation and initiation resistance mechanisms in the surface layer of a brittle material to the fracture onset resistance level.

Materials with a low *Measure* are shown to be the safest ones (e.g., Ti_3AlC_2, Mg-PSZ TS – at least they do not accumulate much elastic energy for catastrophic fracture). The most hard and fracture tough ones (e.g., glass, Y-TZP-A) would require a thorough protection from the contributor of local stress concentrations to effect their potentials.

REFERENCES

1. G. A. Gogotsi, V. Y. Galenko, and G. de Souza, "Dental Y-TZP ceramics: Local fracture resistance," *Strength Mater*., **53**, No. 3, 471–476 (2021), https://doi.org/10.1007/s11223-021-00308-9.
2. *ISO 23146:2008. Fine ceramics (advanced ceramics, advanced technical ceramics) – Test methods for fracture toughness of monolithic ceramics – Single-edge V-notch beam (SEVNB) method*.

3.   G. A. Gogotsi, "Fracture toughness of ceramics and ceramic composites," *Ceram. Int.*, **29**, 777–784 (2003).

4.   E. A. Almond and N. J. McCormick, "Constant-geometry edge flaking of brittle materials," *Nature*, **321**, 53–55 (1986), https://doi.org/10.1038/321053a0.

5.   G. A. Gogotsi, S. P. Mudrik, and V. I. Galenko, "Evaluation of fracture resistance of ceramics: Edge fracture tests," *Ceram. Int.*, **33**, 315–320 (2007).

6.   G. A. Gogotsi, V. I. Galenko, S. P. Mudrik, et al., "Fracture resistance estimation of elastic ceramics in edge flaking: EF baseline," *J. Eur. Ceram. Soc.*, **30**, 1223–1228 (2010).

7.   G. A. Gogotsi, "Classification of ceramics and glass (edge chipping and fracture toughness)," *Ceram. Int.*, **40**, 5591–5596 (2014).