

APPLICATION OF THE SINGLE IMPACT MICROINDENTATION FOR NON-DESTRUCTIVE TESTING OF THE FRACTURE TOUGHNESS OF NONMETALLIC AND POLYMERIC MATERIALS

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At present time the technical progress gives new requirements to engineering materials and this leads to gradual replacement of metals with polymers and composites. Most intensively this process occurs in the automobile and aviation industry and specialists evaluate that by 2020 their part in the elements of load-bearing structures will reach 40-50%. In this connection it becomes necessary to evaluate the properties of such materials not only at their manufacture but also during exploitation. One of the most important parameters of the material responsible for its exploitation reliability is fracture toughness. As a rule, fracture toughness is determined on specially produced samples. For materials and products of small size such methods are inapplicable, besides they also do not allow to perform control of real products. The best solution in this case is application of indentation and analysis of cracks formed at intrusion of axisymmetric indenter into the material. In this connection a task has been set in this paper to determine applicability of the indentation method for evaluation of fracture toughness for elastoplastic polymer materials and for polymethyl methacrylate (PMMA) in particular.

The samples of PMMA type TOSP-2 has been selected as test objects. This material is optically transparent which allows to trace the process of fracture. Indentation was carried out in the static and dynamic mode. Static loading was performed on the Vickers hardness meter. The hardness meter was additionally equipped with LED sensor which allowed to measure hardness at loading as well as after its removal. Measuring of the intrusion depth was conducted with precision of 10 μm .

In the dynamic mode the material is loaded by indenter that falls free at the moment of impact. At the same time the device specially designed for these purposes allowed to record not only the final parameters of the impact impulse: maximum intrusion α_{max} , maximum contact force P_{max} , initial velocity v_{max} , rebound velocity $v_{\text{отскока}}$, impact time t and etc., but also the entire loading process.

The indenter gained velocity v_{max} could be changing in the range from 0,2 to 3 m/s.

During tests conical indenters were used with mass of $m=6,4 - 11,5$ g. made from tungsten carbide with the tip angle of $\varphi=90$ and 120 degrees. With such indenter form the cracks in the material appear at a lower velocity v and loading P of intrusion, as compared to using of spherical tips. Figure 1 shows the character of cracks, formed in PMMA during intrusion of indenters. Developing of cracks was performed in the technical acetone medium. The character, length l and quantity n of cracks, that are formed at intrusion considerably depended on the extent and strain rate and also on the angle of cone opening. Optical measurings that were conducted at static indentation showed that formation of the radial crack occurred on the stage of loading with its further growth on the stage of unloading. One of the first papers in which the fracture toughness was evaluated was the Palmqvist work [1]. He showed that calculations should account for the overall amount of cracks and determined dependence between the total length of radial cracks l , load P , applied to the indenter and fracture toughness.

$$\sum_i^n l_i = b_1 P - b_2, \quad (1)$$

where b_1 and b_2 – parameters associated with the crack resistance and the state of the surface.

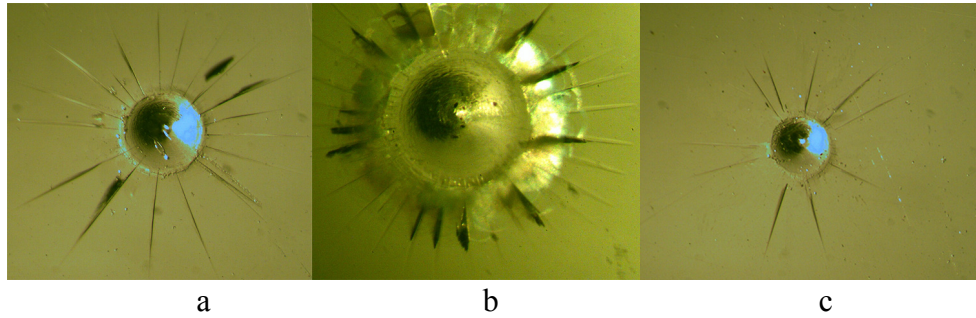


Fig. 1. Cracks, formed in PMMA during intrusion of indenters. a - the static indentation with the formation of radial cracks, b - the static indentation with the formation of lateral and radial cracks, c - under dynamic loading with the formation of radial cracks

In our calculations as the base were also taken the results of indentation at which it was possible to observe formation of Palmqvist radial cracks only, i.e. in conditions when median and lateral cracks were absent. For description of the fracture process an energetic approach was used for calculation of sizes for spalling fragments at formation of median cracks. Let's use this approach for calculation of the critical stress intensity factor K_{Ic} , at formation of Palmqvist radial cracks (Fig. 2).

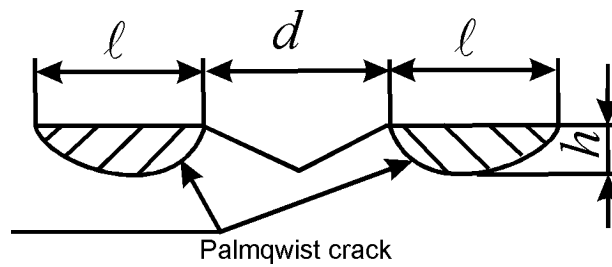


Fig. 2. Palmqvist crack.

In the [2] the following equation for stress intensity factor for crack with length l was derived:

$$K_I = \frac{1,12\sqrt{\pi}\sigma h}{\sqrt{2l}}, \quad (2)$$

Where σ – stress, acting the crack, h - depth of the crack, the geometry of which can be described by means of a semiellipse.

If several cracks are formed their overall length can be replaced with multiplying of the cracks quantity n on their average length l_{av} :

$$K_I = \frac{1,12\sqrt{\pi}\sigma h}{\sqrt{2nl_{av}}} \quad (3)$$

Formation of the radial cracks occurs as a result of tensile circumferential stress σ_θ , the exact calculation of which is a difficult problem. It can be accepted equal to the normal σ_n if the Harr-Carman condition is met or they can be calculated if it is accepted that the maximum circumferential stress appears at the border of the elastoplastic transition in accordance with approach suggested in [3, 4]. In the second case which has a better theoretical background, σ_θ is described through yield stress σ_T [5]:

$$\sigma_{\theta} = \frac{\sigma_T}{3} \quad (4)$$

Taking into consideration the relation between σ_T and material hardness H :

$$H \approx 3\sigma_T, \quad (5)$$

We will get:

$$\sigma_{\theta} = \frac{H}{9} \quad (6)$$

Material hardness, as the average contact pressure $H = \frac{4P}{\pi d^2}$ for the cone with arbitrary tip angle is also equal to the unit work of displacement of materials volume V :

$$H = \frac{A}{V} = \frac{4P}{\pi d^2}, \quad (7)$$

Where d – impression diameter, A –work of straining, that can be derived through the kinetic energy of the falling indenter:

$$A = \frac{m v_{\max}^2}{2} \quad (8)$$

Taking into consideration that the displacable volume of the material is approximately equal to the cone volume, indented into the material tested on the depth α :

$$V = \frac{\pi d^2 \alpha}{12}, \quad (9)$$

and also accepting the fact that the depth of the radial crack (fig. 2), as a rule, does not exceed the penetration depth [2] $h \approx \alpha = d / (2 \operatorname{tg}(\varphi / 2))$, by using equations (3), (6)-(9), we can obtain:

$$K_{lc}^{\partial} = 0,3 \frac{m v_{\max}^2}{d^2 \sqrt{n l_{cp}}} \quad (10)$$

And for static indentation:

$$K_{lc}^s = 0,099 \frac{P}{d \sqrt{n l_{cp}} \operatorname{tg}(\varphi / 2)} \quad (11)$$

If it is considered that the purpose of this paper was to investigate the possibility of applying the method for determination of K_{lc} , and at the same time a task was not set to obtain true value of fracture toughness, then accepted assumptions concerning the stress value, which affects the crack, are completely justified. Besides in [5] was determined that the stresses in the area of contact under the loading as well as after its removal (residual stresses) are proportional for the material hardness. Table 1 shows the results of static tests of PMMA with various indenters at different conditions of loading and temperature T .

Table 1

$P, \text{ Н}$	50	100	150	250
$T, ^\circ\text{C}$	25			
$\varphi, \text{ град}$	90			
$K_{lc}^s,$ $\text{КПа}\sqrt{M}$	67,9±18	65,2±18	71,9±19	
$\varphi, \text{ град}$	120			
$K_{lc}^s,$ $\text{КПа}\sqrt{M}$	74,7±19	71,0±17	72,2±16	79,3±12
$T, ^\circ\text{C}$	0			
$\varphi, \text{ град}$	90			
$K_{lc}^s,$ $\text{КПа}\sqrt{M}$	114±18	127±17	0,119±21	
$\varphi, \text{ град}$	120			
$K_{lc}^s,$ $\text{КПа}\sqrt{M}$	129±19	127±14	121±21	134±11

As seen from the table the values of K_{lc}^s do not depend on the loading rate, but significantly change because of the temperature. Increase of fracture toughness is observed with decrease of temperature. Behavior of the dynamic fracture toughness was considerably different (fig. 3). For the range of average strain rates achieved during measurements $\varepsilon'_{cp} = 2v_{\max}/(\alpha_{\max} \text{tg}(\varphi/2))$ no clear tendency for change depending on the strain rate was observed. At the same time K_{lc}^{∂} has decreased as the temperature T went down.

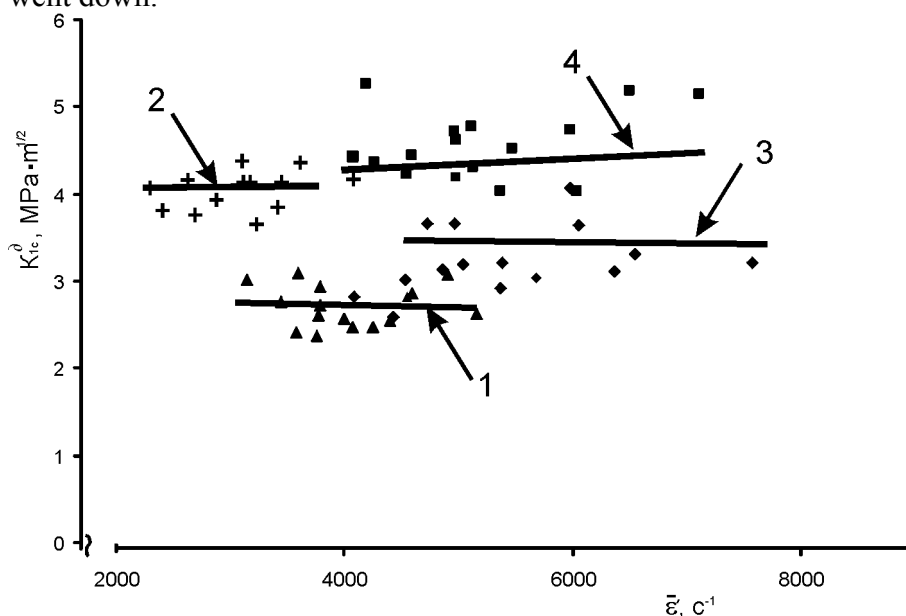


Fig. 3. Dependence of the $K_{lc}^{\partial} = f(\bar{\varepsilon})$ at the testing of PMMA. (1 — $\varphi=90^\circ$, $T=-10^\circ\text{C}$; 2 — $\varphi=90^\circ$, $T=25^\circ\text{C}$; 3 — $\varphi=120^\circ$, $T=-10^\circ\text{C}$; 4 — $\varphi=120^\circ$, $T=25^\circ\text{C}$).

Nevertheless, obtained results correspond to the common experimental data. In [6,7] it is shown that strain rate and temperature can significantly influence the value K_{lc} . Hence, the obtained results

show that the given method can be used at tests of elastoplastic polymer materials. The disadvantage of this method is the difficulty of determining quantity and size of cracks, that requires application of additional equipment -microscopes and penetrants for revealing of cracks, which also adds significant inaccuracy of measurements. However an undoubted advantage of this method is the ability to control the real products without manufacture of samples when applying dynamic indentation. This method has become widely used for control of hardness and devices based on application of impact on the tested material by indenter are widely available. Besides, at the appropriate calibration (account of strain rate and temperature) it is possible to reduce these values to those obtained by standard testing scheme.

References

1. *Palmquist S.* / Jernkontorents Ann. 1963. Bd. 147. № 1. S 107—110.
2. *Niihara K. A.* / Journal of materials science letters. 1983. № 2. P. 221—223.
3. *Bishop R. F.* / Proc. Phys Society. 1945. № 57. P. 147—159.
4. *Marsh D. M.* / Proc. Phys. Society. 1964. F 279. P. 420—435.
5. *Johnson K. L.* / J. Mech and Phys Solids. 1970. № 18. P. 115—126.
6. *Marshall G. P.* // Journal of material science. 1974. № 9. P. 1409-1419.
7. *Atkins A.G.* / Journal of material science. 1975. № 10. P. 1381—1393.