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 have 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 $\alpha_{\text{max}}$, maximum contact force $P_{\text{max}}$, initial
velocity $v_{\text{max}}$, rebound velocity $v_{\text{rebound}}$, impact time $t$ and etc., but also the entire loading process.
The indenter gained velocity $v_{\text{max}}$ 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.

$$\sum l_i = b_1 P - b_2 ,$$

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.](image)

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

$$K_I = \frac{1.12\sqrt{\pi \sigma h}}{\sqrt{2l}},$$  \hspace{1cm} (2)

Where $\sigma$ – 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 $l_{av}$:

$$K_I = \frac{1.12\sqrt{\pi \sigma h}}{\sqrt{2nl_{av}}}$$  \hspace{1cm} (3)

Formation of the radial cracks occurs as a result of tensile circumferential stress $\sigma_\theta$, the exact calculation of which is a difficult problem. It can be accepted equal to the normal $\sigma_n$ 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, $\sigma_\theta$ is described through yield stress $\sigma_T$ [5]:
\[ \sigma_\theta = \frac{\sigma_T}{3} \]  

(4)

Taking into consideration the relation between \( \sigma_T \) and material hardness \( H \):

\[ H \approx 3 \sigma_T, \]  

(5)

We will get:

\[ \sigma_\theta = \frac{H}{9} \]  

(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 \( V \):

\[ H = \frac{A}{V} = \frac{4P}{\pi d^2}, \]  

(7)

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

\[ A = \frac{m v_{\text{max}}^2}{2} \]  

(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 \( \alpha \):

\[ V = \frac{\pi d^2 \alpha}{12}, \]  

(9)

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

\[ K_{lc} = 0.3 \frac{m v_{\text{max}}^2}{d^2 \sqrt{n l_{cp}}} \]  

(10)

And for static indentation:

\[ K_{lc} = 0.099 \frac{P}{d \sqrt{n l_{cp} \tan(\varphi / 2)}} \]  

(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 \( T \).
As seen from the table the values of $K_{ic}$ 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 measuring $\dot{\varepsilon}_\phi = 2\nu_{\max}/(\alpha_{\max} \cdot \tan(\phi/2))$ no clear tendency for change depending on the strain rate was observed. At the same time $K_{ic}$ has decreased as the temperature $T$ went down.

![Fig. 3. Dependence of the $K_{ic} = f(\varepsilon)$ at the testing of PMMA. (1 — $\phi=90$, $T=-10$ °C; 2 — $\phi=90$, $T=25$ °C; 3 — $\phi=120$, $T=-10$ °C; 4 — $\phi=120$, $T=25$ °C).](image)

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 $K_{ic}$. 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