The tensile strength diagnostics of transparent monolithic polycarbonate by piezoelectric effect

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Abstract. The experimental results of relationship between tensile strength and piezoelectric voltage in transparent monolithic polycarbonate are presented in that paper. The most useful location of electrodes on the surface of monolithic polycarbonate samples for measurement the piezoelectric voltage was determined. It was showing that the first derivative of piezoelectric voltage by time passes through the zero when the cracks in polycarbonate start arising. Moreover, the local maximums of the piezoelectric voltage and a tensile strength come a little bit earlier than the cracks in polycarbonate start arising. That allows using piezoelectric effect to diagnostics the maximum allowable strength in transparent monolithic polycarbonate.

The diagnostics of strength characteristics (for example, maximum allowable strength) of organic glasses (transparent monolithic polycarbonate or polymethylmethacrylate) should be used in same practices application, as an aircraft cockpit glazing, building stained-glass windows, glass roofs. That because of hardness organic glass decrease under such external influences as irradiation with solar radiation [1, 2], wind and snow loads [3, 4], temperature changes [5, 6], and aging of the material [7]. For example, in [8] it was shown that, after UV radiation exposed for 3050 hours and relative air humidity of 42%, the number average molecular weight decreases by 6%, and the mass average molecular weight decreases by 3.2%, that indicate the occurrence of backbone breaking in polycarbonate.

The lack of changes in the construction of organic glass and saving the view through glass is the main criteria of its strength diagnostic methods choosing. The promising method for such diagnostics is based on the piezoelectric effect in polymers [9]. The macromolecules polarization in polymers by the change in their mutual arrangement under external mechanical influences is underlie of the piezoelectric effect in polymers (for example in organic glasses) [10]. So, the piezoelectric effect in organic glasses is determined by the structure and its changes [11, 12]. Therefore, the relationship between piezoelectric voltage and structure changings in the organic glass under the external force can allowed to diagnostic the tensile strength decrease. This differs from strain gauges measuring actual mechanical deformation [13]. The piezoelectric effect in polymers is rather well studied [14-17, 18]. However, there are no data in the literature on the influence of the measurement circuit (the location, area and geometry of the electrodes) on the relationship between mechanical stresses and piezoelectric voltage in monolithic polycarbonate. The purpose of this work is to determine the influence of the location of the electrodes for measuring piezoelectric stress on the possibility of diagnosing the tensile strength of monolithic polycarbonate.
Two series of experiments were conducted to determine the effect of the location of the electrodes on the results of measuring the piezoelectric voltage at various loads and to assess the possibility of diagnosing the tensile strength of monolithic polycarbonate.

The influence of the electrodes location on the results of piezoelectric stress measurements (U) was investigated in the first series of experiments. Electrodes were deposited by spraying a surface of an electrically conductive copper coating on the samples surface (monolithic polycarbonate Novattro 100x100 mm, thickness of 3 mm). Electrode deposition schemes are shown in figure 1. Samples of figure 1d are made to check the reproducibility of the measurement results.

Measurements were carried out on each of the samples at least 20 times. The number of samples of each type is 10 pieces. The samples (figure 1) were subjected to three-point bending on a Shimadzu testing machine with simultaneous measurement of the piezoelectric stress. The measurement scheme is shown in figure 2.

The following notation is used in figure 2: P is the force with which the deformed sample acts on the rod 1; U is the piezoelectric voltage measured from the electrodes.
Samples were isolated from supports using a dielectric (fluoroplastic film). The electric voltage $U$ was measured with a V7-78 / 1 voltmeter, measurement error was $\leq 10\%$. The results of measurements of the force $P$ were processed using TRAPEZIUM X software. With this in mind, the measurement error of $P$ was $\leq 5\%$. The samples were loaded at a speed of $v = 10$ mm / min; the electrical voltage was measured during loading of the samples until they were destroyed. The measurement results are shown in figure 3, where figure 3a corresponds to samples 1a, figure 3b to 1b, figure 3c to 1c. The dashed line in figure 3 marks the region of visible cracking in the samples of monolithic polycarbonate due to the applied load.

![Figure 3](image_url)

**Figure 3.** Typical time dependences of normalized loading forces $P$ (1) and piezoelectric stress $U$ (2).
The voltage $U$ was normalized on the average maximum value, which in the experiment amounted to: for electrodes deposited according to the scheme in figure 1a - $U_{1av max} = 1.75 \pm 0.1$ V; according to the scheme of figure 1b - $U_{2av max} = 3.76 \pm 0.22$ V; according to the scheme figure 1c - $U_{3av max} = 4.2 \pm 0.2$ V.

The electrodes arrangement in figure 1c showed the best correspondence of force and piezoelectric voltage. Most likely, this is due to the distribution of the sign of the piezoelectric potential over the surface of the sample [19]. The destruction of bonds between molecules in polycarbonate leads to a decrease in piezoelectric stress. The mutual displacement of polycarbonate molecules decreases after the formation of cracks; as a consequence, the polarization of the molecules decreases. Apparent cracking occurred 70–80 s after the start of the experiment. It should be noted that schemes in the region of noticeable cracks (figure 3), the first derivative of the piezoelectric voltage ($dU/dt$) passes through zero for all electrode deposition. Overall, turning the derivative $dU/dt$ to zero is one of the sufficient conditions for predicting the destruction of the material. The global maximum of the piezoelectric stress and load force functions precede the beginning of the region of appearance of visible cracks for all samples, except for figure 1b.

A studying of the reproducibility of measurement results was carried out in the second series of experiments. Maintaining structural integrity is crucial to evaluate reproducibility. Therefore, the samples (figure 1d) were loaded in the region of linear characteristics (figure 3), for 35 s (loading speed $v = 10$ mm / min). Then, the load was removed from the samples to avoid changes in the structure of the material. The electrical voltage was measured during loading of the samples. The experiment was repeated on the same samples after 24 hours. Typical measurement results are presented in figure 4. The piezoelectric voltage $U$ was normalized to the average maximum value, which in the experiment was: electrode 1 (figure 1d) - $U_{1av max} = 3.912 \pm 0.234$ V; electrode 2 (figure 1d) - $U_{2av max} = 1.474 \pm 0.088$ V; electrode 3 (figure 1d) - $U_{3av max} = 0.916 \pm 0.054$ V.

![Figure 4](image_url)

**Figure 4.** Typical time dependences of the normalized piezoelectric voltage $U$ (1 - initial values, 2 - after 24 hours) for the electrodes of the samples in figure 1d: electrode 1.

Studies have shown that the absolute values of the measured piezoelectric stress are different from sample to sample. This difference can be explained by structural features of monolithic polycarbonate, for example, crystallinity [20]. However, a monotonous increasing characteristic is well reproduced in all cases, during repeated measurements; the measurement error did not exceed ~ 10%.

It was shown that the best correspondence of piezoelectric stress and the force with which the deformed sample acts on the rod could be provided by the electrodes arrangement (figure 1c). The monotonicity of the piezovoltage characteristic, the global peak of the piezoelectric stress before the occurrence of noticeable cracking, as well as the zeroing of the derivative of the piezoelectric stress in the cracking region, allows using the method under consideration for diagnosing the tensile strength of monolithic polycarbonate during its operation.

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