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Localized impact damage of polymethylmethacrylate at temperatures lower and higher than the glass transition point

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A shock wave in the polymethylmethacrylate was excited with a sharpened-pendulum-type testing machine. The energy yield stimulated by the material strain and microcracking in the locally damaged surface was detected by the acoustic emission (AE) method in the frequency ranges of 80−200 and 600−800 kHz. The low-frequency AE series were attributed to the polymer deformation, while the high-frequency emission was related to microcracking. The experiments were conducted in the temperature range from room temperature to 110°C which is slightly higher than the glass transition point (104°C). Relative contribution of the strain energy was prevalent at all the temperatures. At the temperatures higher than the glass transition point, some signs of strain hardening appeared.

Keywords: polymethylmethacrylate, impact damage, acoustic emission.

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Due to such properties as strength, density and transparency, as well as relatively low cost, thermoplastic polymer polymethyl methacrylate (PMMA) finds its place in a wide range of technical applications: from smartphone screens and displays to car and aircraft windows/portholes [1]. When PMMA products are to be mounted on front openings of high-speed mobile devices, especial attention should be paid to their shock strength [2–4] because they are subject to impacts from solid particles and rainfalls [5,6]. To monitor the behavior of various materials subjected to mechanical load, the acoustic emission (AE) method is widely used, which is based on sensitivity to elastic waves arising in micromechanical events induced in solids. In this work, the time series of AE pulses arising due to mechanical impact to PMMA plates and reflecting the processes of microdeformation and microcracks accumulation in the material has been analized.

At the temperatures below the glass transition point $T_g = 104$°C, PMMA is a brittle impact-resistant plastic. In this temperature range there are several intervals specific to the polymer mechanical properties: conventionally, PMMA are operated in a wide temperature range from −45 to 70°C; from above 70°C and up to the glass transition point, the polymer softening takes place; in a narrow range of 104−115°C, strain hardening occurs under the mechanical impact to the material; at 120°C, the polymer begins exhibiting the fluid medium characteristics. In this work, measurements were performed at sample temperatures of 20°C (the most often used one), 80°C (above the characteristic operating range), and 110°C (strain hardening).

As the sample temperature increases and overcomes the glass transition point, it could be expected that shock-excited series of AE pulses generated due to deformation and microcracking make different contributions to the time, frequency, and energy characteristics. Therefore, acoustic sensors should be chosen so as to cover a sufficiently wide frequency range that is 50−1000 kHz in the case of polymer destruction [8].

Using resonant sensors, it is possible to detect weaker signals, but only in a narrow frequency range. Broadband sensors cover virtually the entire set of defects forming in the polymer, but they are less sensitive. Besides, the broadband AE analysis provides an averaged pattern of the energy release in AE pulses, which is free of differentiation between high and low-energy signals that are, probably, of different origins. Hence, their contributions to sound emission lie in different frequency ranges. This issue may be overcome by simultaneously using two or more narrow-band sensors [9]; however, there arises a problem of mismatch of technical characteristics of several resonant receivers.

In case PMMA is exposed to a mechanical impact, two energetically different processes are observed: deformation and microcrack accumulation; this leads to AE generation in various frequency ranges. Therefore, in this study sources of various-origin elastic waves were identified by analyzing data from a highly sensitive piezoelectric sensor made of the $Pb(Zr_xTi_{1-x})O_3$ ceramics in two ranges, 80−200 and 600−800 kHz. Thus, the energy release due to deformation and microcrack formation initiated by a local impact was detected by a single AE receiver, which reduced instrumental distortion of measurements. Low-energy (low-frequency, LF) generation was attributed to the structure deformation, while high-energy (high-frequency, HF) generation was related to destruction.

AE signals were fed, through analog-to-digital converter ASK-3106, to the computer memory with time resolution of 40 ns. Duration of the emission activity detection was 2 ms.

The sample was heated to temperatures of 80 and 110°C by using an air dryer.

In the experiments, commercial sheet PMMA (organic glass) obtained by the bulk polymerization method was used. Localized damage of the samples was performed using a sharpened-tip pendulum-type testing machine. The chosen damage-initiation method allowed obtaining localized surface destruction in a spot of ~ 1 mm in diameter with a well-reproducible morphology.

Fig. 1 presents the scans of the acoustic response to room-temperature point damage to the surface. Since the AE signal includes both negative and positive pulses, here are presented squared amplitudes proportional to the energy yield.

One can see that, when the applied impact energy was minimal ($E = 0.06$ J) (Fig. 1, *a*), intensities of LF and HF emissions in the first 0.5 ms after the impact were approximately the same, but fast attenuation of the microcrack-induced HF signal was observed. Duration of the strain-induced LF signal was within the time scan duration of 2 ms.

When the impact energy was increased to $E = 0.12$ J (Fig. 1, *b*) and 0.25 J (Fig. 1, *c*), short-term bursts of LF emission occurred, while the HF signal remained at the noise-track level. At the same time, the LF AE peak intensity exceeded that at the minimum impact energy ($E = 0.06$ J, Fig. 1, *a*) by an order of magnitude. Thus, the room-temperature damage of material occurred mainly due to the structure deformation.

At the sample temperature of 80°C (i.e. beyond the upper limit of the PMMA operating range) and impact energy of $E = 0.06$ J (Fig. 2), the AE scans qualitatively repeated the pattern with the HF signal attenuation and LF signal retention until the time scan end. However, in the latter case (80°C) the AE intensity in both frequency ranges increased by about an order of magnitude. In contrast to the room-temperature AE scans, no isolated high-energy emissions were observed.

Upon the impact $E = 0.06$ J in energy (Fig. 3, *a*) at the sample temperature of 110°C, i.e. above the glass transition point but within the temperature range of strain hardening (104–115°C [7]), the AE pattern was approximately the same as at 80°C. However, when the impact energy increased to 0.25 J (Fig. 3, *b*), the AE intensity increased by an order of magnitude, and a burst of HF emission appeared in the initial scan region. The short-term increase in emission caused by cracking at temperatures above T_g may be explained by a slight increase in the material brittleness in the strain-hardening temperature range. Thus, the frequency differentiation of AE signals in the case of a point impact damage to PMMA made it possible to separately reveal the sound generation initiated by PMMA deformation and cracking. At the sample temperatures below the glass transition point, AE generation due to microcracking lasted for no more than 0.5 ms and then quickly attenuated, while the emission activity excited by the material deformation continued throughout the entire

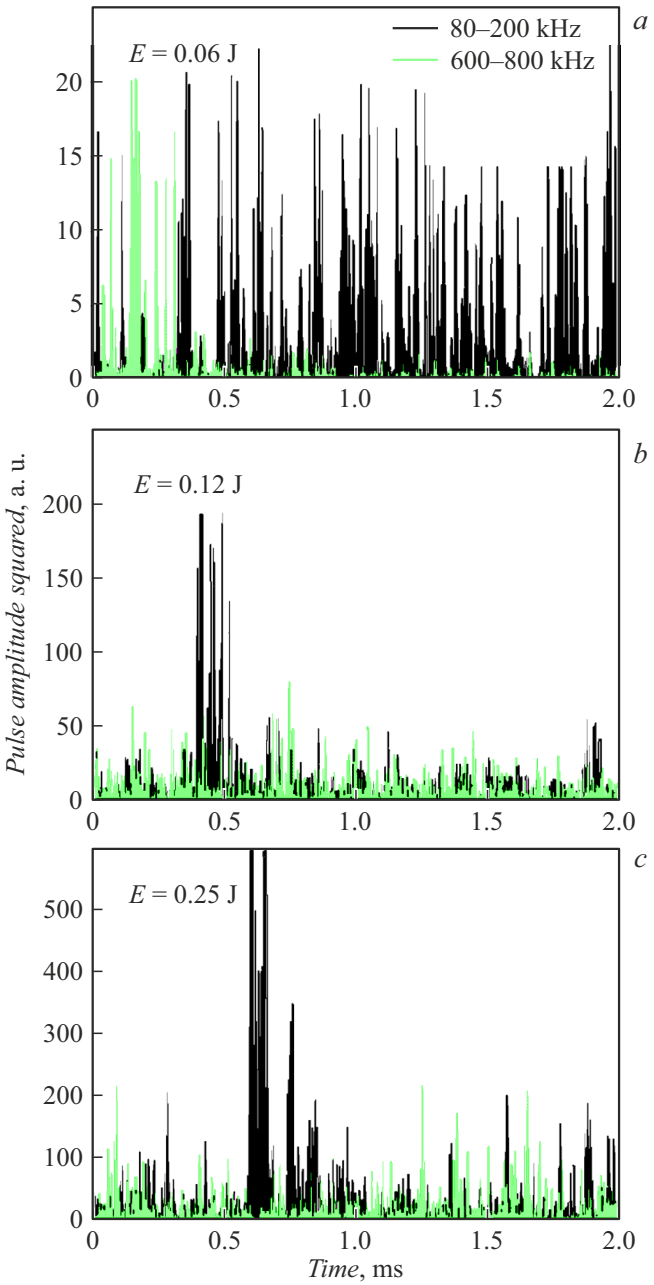

Figure 1. Time scans of AE amplitudes in the ranges of 80–200 and 600–800 kHz, which were recorded in the case of damages by impacts with energies of 0.06 (*a*), 0.12 (*b*) and 0.25 J (*c*) produced at the sample temperature of 20°C. The colored figure is given in the electronic version of the paper.

scanning period (2 ms). In the strain-hardening temperature range (104–115°C), a short-term AE signal associated with destruction of the unstable ordered structure of oriented polymer chains was observed. In general, the measurements have shown that, under the conditions of a point impact, damage to amorphous PMMA at the temperatures from room temperature to 110°C occurs predominantly due to deformation of the material with a minor contribution from cracking.

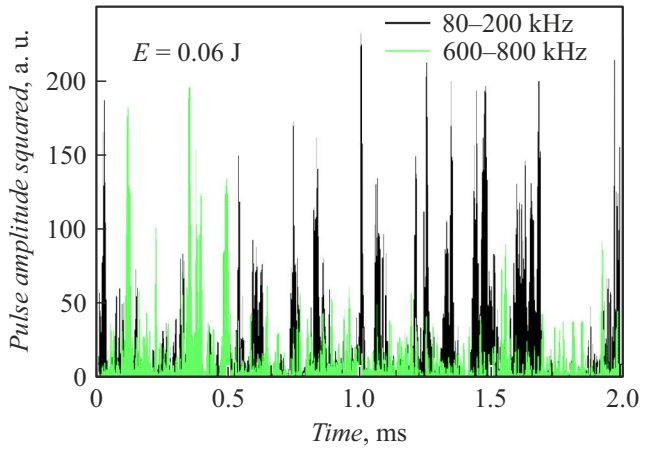

Figure 2. Time scans of AE amplitudes in the 80−200 and 600−800 kHz ranges recorded for the case of damage by the impact 0.06 J in energy at the temperature of 80°C. The colored figure is given in the electronic version of the paper.

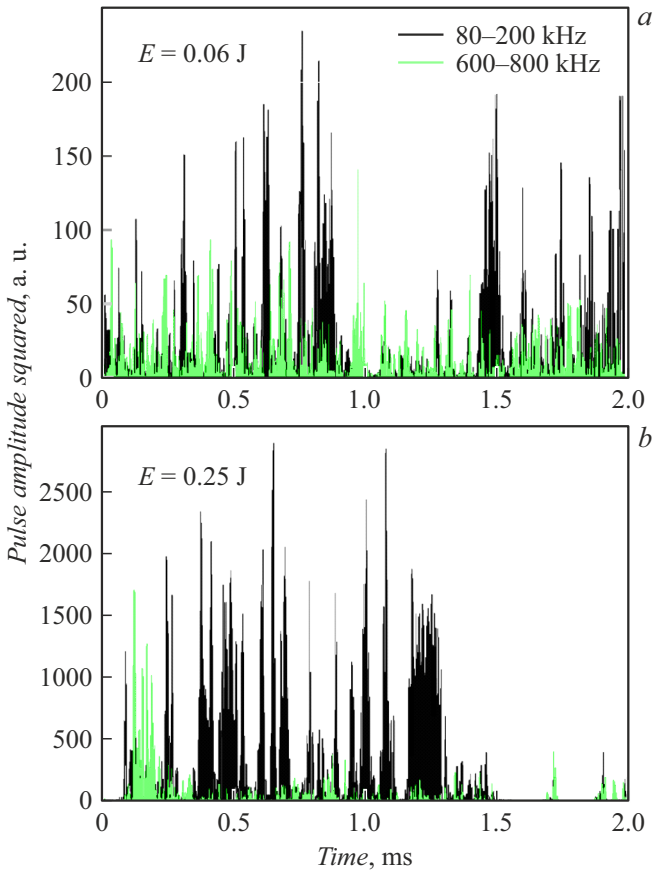

Figure 3. Time scans of AE amplitudes in the ranges of 80−200 and 600−800 kHz, recorded in the case of damages produced by impacts with energies of 0.06 (*a*) and 0.25 J (*b*) at the temperature of 110°C. The colored figure is given in the electronic version of the paper.

Conflict of interests

The authors declare that they have no conflict of interests.

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