Combustion, Explosion, and Shock Waves, Vol. 39, No. 2, pp. 240–242, 2003

URGENT COMMUNICATION

Observation of Compression and Failure Waves in PMMA by Means of Synchrotron Radiation

P. I. Zubkov,[1] G. N. Kulipanov,[2] L. A. Luk'yanchikov,[1] L. A. Merzhievskii,[1] K. A. Ten,[1] V. M. Titov,[1] B. P. Tolochko,[3] M. G. Fedotov,[2] M. R. Sharafutdinov,[2] and M. A. Sheromov[2]

UDC 539.411.5

Translated from *Fizika Goreniya i Vzryva*, Vol. 39, No. 2, pp. 137–139, March–April, 2003.
Original article submitted November 20, 2002.

The possibility of using synchrotron radiation for density measurements in shock-compressed polymethylmethacrylate destroyed in a failure wave is demonstrated for the first time. Parameters of the compression and failure processes are presented.

Key words: failure wave, shock wave, synchrotron radiation.

The possibility of using x-ray synchrotron radiation (SR) for studying detonation and shock-wave processes were discussed in [1]. The most important unique properties of the generated radiation from the viewpoint of research problems formulated are the small angular divergence and high intensity of the flow, small duration of the radiation pulse (less than 1 nsec) and, hence, exposure time, and stability of intervals of the generated pulses. The main SR parameters obtained at the Institute of Nuclear Physics of the Siberian Division of the Russian Academy of Sciences and the test bench for explosion and shock-wave experiments are described in [1].

To demonstrate SR capabilities for diagnostics of shock-wave processes in solid inert media, polymethylmethacrylate (PMMA) was chosen as an object of investigation, which possesses a number of versatile physical and mechanical properties under such loading. Depending on loading conditions, this material can be elastic, elastoviscoplastic, or elastobrittle [2]. In the latter case, its failure can occur in the form of a brittle failure wave propagating over the compressed specimen. Despite the large number of experimental and theoretical papers dealing with the properties and behavior of this and other materials with similar properties (mainly, glasses), there are no well-established physical concepts of this process (physical model) and, hence, adequate mathematical model. Almost all key issues of the mechanisms of shock-wave compression and failure-wave emergence and evolution remain open [3]. For instance, it remains unclear which cracks (longitudinal or transverse shear) are determining for the failure wave. This circumstance makes urgent obtaining new information on the structure and kinetics of compression and failure waves.

The intensity of the x-ray beam passing through the specimen and varied with changing density of the material was measured in the experiments [1]. The layout of the experiments is shown in Fig. 1. Cylindrical PMMA specimens 10 mm high were loaded on one butt-end face by exploding a 50/50 TNT/RDX high explosive (HE) charge of the same shape and 70 mm high. The opposite butt-end face of the specimen contacted a steel cylinder 20 mm long. The diameters of all elements of the experimental setup were 10 mm. The zone where the SR beam was introduced (3 in Fig. 1) was a square

[1]Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090; merzh@hydro.nsc.ru.
[2]Budker Institute of Nuclear Physics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090.
[3]Institute of Chemistry of Solids and Mechanochemistry, Siberian Division, Russian Academy of Sciences, Novosibirsk 630128.

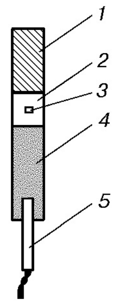

Fig. 1. Layout of experiments: 1) metal cylinder; 2) PMMA specimen; 3) zone of introduction of the SR beam; 4) HE charge; 5) detonator.

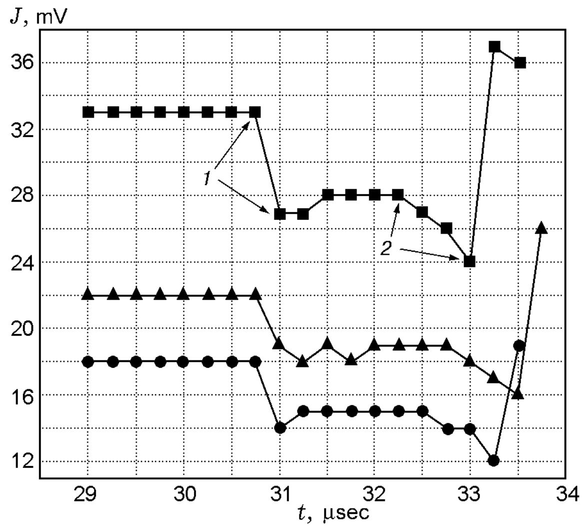

Fig. 2. Time evolution of intensity of the transmitted SR beam: 1) shock wave; 2) compression in the failure wave; the points ■, •, and ▲ refer to the first, second, and third channels of the detector, respectively.

2×2 mm; the cross-sectional size of the SR beam was 2×1.5 mm. The intensity of transmitted radiation was registered by a microstrip detector [1]. The size of strips in the direction of the specimen centerline was 0.1 mm. Three strips (channels) spaced by 0.2 mm were used in the experiments. The measured intensity of transmitted radiation (material density) is plotted in Fig. 2 in the form of dependences of intensity on time with a measurement interval of 0.25 μsec; the "background" of the detector strips, which was variable, generally speaking, was measured in between. The record clearly shows compression in the shock-wave front (the peak of intensity corresponds to the peak of density) with a failure wave following after a certain time. After that, an increase in intensity (decrease in density) corresponding to spreading of fragments formed in rarefaction waves is observed.

The data obtained allow us to make quantitative estimates of the parameters of the process observed. The intensity of the transmitted beam J is related to the intensity of the initial beam J_0 as

$$J = J_0 \exp(-k\rho d), \qquad (1)$$

where d is the specimen size in the direction of the beam, ρ is the density of the material, and k is the attenuation factor. Special experiments were performed to determine k, where a beam of constant initial intensity was transmitted through unloaded specimens of different thickness d. In this case, we have

$$k = \frac{1}{\rho_0 d} \ln \frac{J_0}{J},$$

where ρ_0 is the density of the uncompressed material. Assuming that k is constant, we obtain $k \approx 0.65$ cm^2/g on the basis of our data.

In addition, the shock-wave velocity D excited in the specimen under study by the HE charge was measured using simple contact gauges. We obtained $D \approx 4.3$ km/sec on a base of 10 mm. Since the PMMA shock adiabat in the form of the dependence $D = a + bu$ (u is the mass velocity and a and b are constants) is known [4], we can obtain two independent estimates for compression parameters in the shock wave registered in Fig. 2: using Eq. (1) and the above-derived value of k ($\rho/\rho_0 = 1.31$) and using the shock adiabat ($\rho/\rho_0 = 1.35$), which demonstrate rather good accuracy reached in SR measurements.

As is seen from Fig. 2, a further increase in density occurs in the failure wave propagating behind the shock wave with an interval of 1.25 μsec. The effect of compaction of brittle materials in the failure wave is known [5], but it seems to be observed for the first time for PMMA. Compression lasts for $\approx$0.75 μsec, until dispersion of the destroyed medium, which lost tensile and shear strength, begins under the action of rarefaction waves. The maximum compression reached was $\rho/\rho_0 \approx 1.52$. The failure-wave velocity calculated from experimental data is $D_R = 0.8$ km/sec, which is in good agreement with the known estimate [3] $D_R \approx 0.5C_t$, where $C_t = 1.4$ km/sec is the transverse velocity of sound. This value of D_R, however, is local; if it were the velocity of the steady failure wave, the simplest calculation shows that the lag between the shock-wave front and failure front should have arisen instantaneously 1.2 mm ahead of the measurement point. It is reasonable to assume that, as in the case of PMMA failure under the explosion of a spherical HE charge inside a Plexiglas box [6], the velocity of the failure front under conditions considered is a decreasing function of the covered distance, asymptotically approaching the steady value $D_R \approx 0.5C_t$.

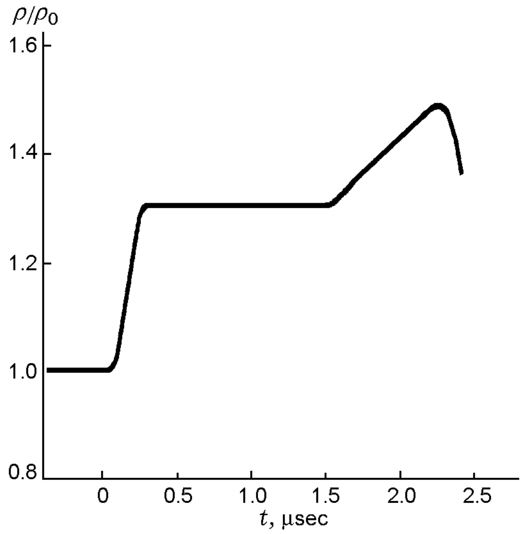

Fig. 3. Distribution of density in time.

For the shock and failure waves, the complete profile of density constructed on the basis of the measurement results (see Fig. 2) is plotted in Fig. 3. Qualitatively, it corresponds to the stress profile in glass, which was observed in a similar process [5].

Summarizing the above facts, we can state that the analysis of density-measurement results in shock-compressed PMMA by means of synchrotron radiation gave an idea of the dynamics of compression (shock) and failure waves, which is in complete agreement with available concepts of the evolution of the phenomenon under consideration. Thus, SR applicability for studying this class of processes was demonstrated for the first time.

This work was supported by the Russian Foundation for Fundamental Research (Grant No. 02–02–16799), Program of Leading Scientific Schools (Grant No. 00–15–96181), and Integration Grant of the Siberian Division of the Russian Academy of Sciences (Grant No. 51).

REFERENCES

1. A. N. Aleshaev, P. I. Zubkov, G. N. Kulipanov, et al., "Application of synchrotron radiation for studying detonation and shock-wave processes," *Combust. Expl. Shock Waves*, **37**, No. 5, 585–593 (2001).
2. L. M. Barker and R. E. Hollenbach, "Shock-wave studies of PMMA, fused silica and sapphire," *J. Appl. Phys.*, **41**, No. 10, 4208–4226 (1970).
3. V. N. Nikolaevskii, "Dynamic strength and failure rate," in: *Shock, Explosion, and Failure* (collected scientific papers) [Russian translation], Mir, Moscow (1981), pp. 166–203.
4. R. G. McQueen, S. P. Marsh, J. W. Taylor, et al., "The equation of state of solids from shock-wave studies," in: R. Kinslow (ed.), *High-Velocity Impact Phenomena*, Academic Press, New York (1970), pp. 293–417.
5. N. K. Bourne and Z. Rosenberg, "The dynamic response of soda–lime glass," in: *Shock Compression of Condensed Matter* (Proc. of AIP Conf., 1995), Part 1, Woodburg, New York (1996), pp. 567–572.
6. V. V. Aldushkin and A. N. Sukhotin, "Destruction of a solid by an explosion," *Prikl. Mekh. Tekh. Fiz.*, No. 4, 94–101 (1961).