doi: 10.56761/EFRE2022.S2-O-046201

Study of processes in polymer targets under high-energy exposure

O. Olkhovskaya[1,], D. Boykov[1], V. Gasilov[1], E. Kazakov[2], S. Tkachenko[3], A. Smirnova[2,3]*

[1]*Keldysh Institute of Applied Mathematics of the RAS, Moscow, Russia*
[2]*National Research Center "Kurchatov Institute", Moscow, Russia*
[3]*Moscow Institute of Physics and Technology, Moscow, Russia*
[*]*olkhovsk@gmail.com*

Abstract. We studied the impact of a powerful relativistic electron beam on polymer targets at energy density up to 1 kJ/cm^2. Experiments were carried out on high current electron accelerator "Kalmar" at beam current up to 45 kA and electron energy up to 300 keV. Laser shadow streak image was used to visualize the dynamics of shock waves in transparent materials. Three-dimensional numerical simulation of gasdynamic phenomena in the diode gap and elastoplastic phenomena that depend on them in the target material was performed using MARPLE3D multiphysics software package. The new technique was designed for end-to-end modeling including heating and evaporation of the target under the action of the electron beam and nonlinear wave processes leading to internal fractures and spalling phenomena in the target material. We use wide-range equation of state for the description of the liquid and solid phases of matter at low temperatures. Appropriate modeling of this complex problem is based on high resolution numerical methods as well as on high performance computing. The implemented computer models are verified by experimental data. The developed software can be used for numerical stress-strain analysis of various structural units loaded by strong pulsed forces and/or energy fluxes.
Keywords: high-current relativistic electron beam, polymeric materials, numerical simulation.

1. Introduction

Polymers and composites are often used as construction materials for aircraft, space, terrestrial transport, and many other industrial applications due to their high strength characteristics and relatively low weight of structures. The impact of powerful energy fluxes on polymer samples, for example, experiments with relativistic electron beams (REB), is an effective method for analyzing the resistance of polymer materials to extreme loads. Because of the complexity of the processes occurring inside the material under such extreme impacts, it is impossible to observe the evolution of all parameters in the sample volume in an experiment. Because of the variety of structural mechanisms the material deformation and the lack of a complete description of their properties, an accurate analytical description of the processes is also impossible today. Therefore, experimental studies of short high intensity impact on polymers are usually accompanied by numerical simulations. Modern tools of modeling thermomechanical effects during pulse loading of polymer samples allow study the details of wave structures as well as zones of material failures.

The novelty of our approach lies in the end-to-end simulation of processes occurring both in the diode gap of the generator of a high-current pulse of relativistic electrons (I ~ 20–45 kA is the beam current, and its duration is 100–150 ns) and in the target irradiated by this REB (240–1000 J/cm^2 are the characteristic values of the surface energy density deposited by the REB into the surface layers of the anode). To do this, we perform both magnetohydrodynamic (MHD) modeling of the plasma torch, which is formed in the diode gap by a substance ablated from the target surface when exposed to the REB, and modeling of the elastoplastic state of the target when shock waves pass through it generated by the energy and dynamic action of the substance during its ablation from the target surface. When solving this coupled problem, it is necessary to use different models for describing the properties of matter in different states (solid, liquid, gaseous, plasma; stable and metastable) and phase transitions between them (melting, evaporation, etc.), and also to take into account the rather large difference in the scale of this complex system. The time scales of the main significant processes can differ by two orders of magnitude: the duration of the REB pulse, as a rule, is about 100 ns, and the duration of the evolution of elastoplastic deformations, after which irreversible destruction of the target can begin, is ~10 μs.

2. Experimental study

We studied the impact of a powerful relativistic electron beam on polymer targets at energy density up to 1 kJ/cm^2. Experiments were carried out on high current electron accelerator “Kalmar” (National Research Center “Kurchatov Institute”, Moscow, Russia) at beam current up to 45 kA and electron energy up to 300 keV.

Laser shadow chronogram was used to visualize the dynamics of the passage of shock waves in transparent materials [1] and to record the plasma dynamics in the diode gap of the generator [2]. The method is based on analysis of the shadow streak image formed by probe laser radiation that passes through a sample.

The setup of the experiment and its optical design were detailed in [1]. The sensitivity of the method was estimated there on samples of polymethyl methacrylate (Plexiglas) and K-8 optical glass. Now we have investigated a sample of epoxy resin exposed to 600 J/cm^2 REB. REB diameter was d = 10 mm, the pulse duration was τ = 150 ns, the target thickness was z = 15 mm, the target diameter was D = 30 mm. The sample was destroyed during the experiment: a volumeric fracture occurred at the axis of the target as well as a spallation on its rear surface.

The obtained laser shadow chronogram is presented at Fig.1. The irradiated surface is z = 0. The time-analyzing slit of the streak camera length was 15 mm (full thickness of the target), but the image near the rear surface z = 15 mm was not reproduced well.

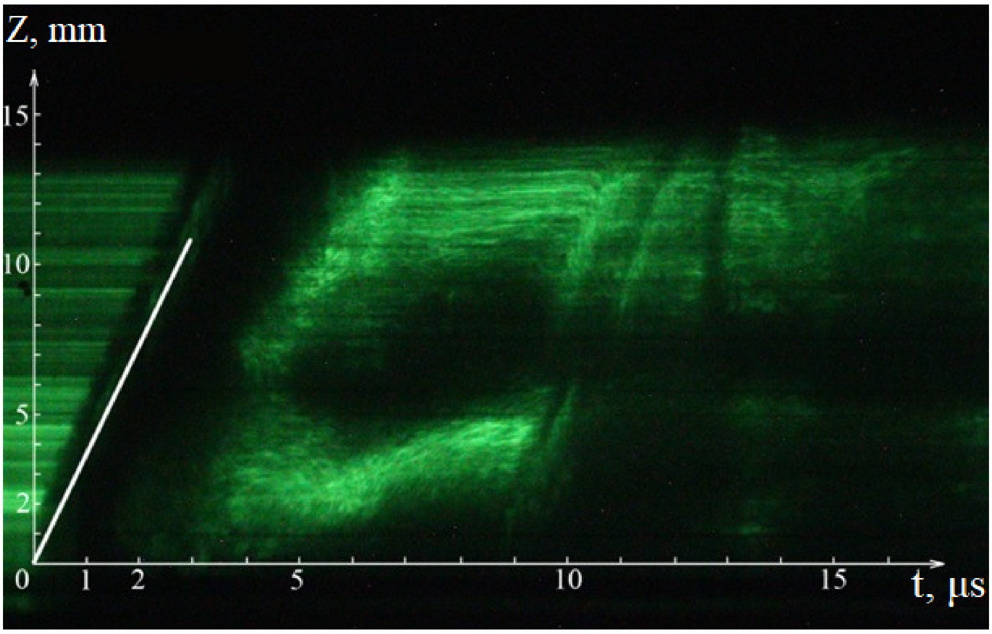

Fig.1. Laser shadow chronogram.

The white incline marks the track of the compression wave occuring in the target. The velocity of the wave front defined by this line is v = 3.6 km/s. The shadow in the centre corresponding the time range 4 μs < t < 10 μs marks a brittle failure in the volume of the target. We think that light spot in the bottom of the shadowgram at 2 mm < z < 5 mm and 3 μs < t < 9 μs is due to some defect of the sample, and does not show the recovery of the material transparency. We were never able to get an acceptable optical quality of the epoxy, it was not even enough, thus it lensed, and this could have a very strong effect on the image. It seems to be the reason why we cannot see the track of the wave reflected from the rare surface of the target. But we see clearly the second wave reflected from the front surface at 9 μs < t < 12 μ with the same front velocity $v \approx$ 3.6 km/s.

3. Numerical simulation

Three-dimensional numerical simulation was performed using MARPLE3D [3] multiphysics software package. We have applied a new technique designed for coupled modeling the action of the REB on the target front surface, hydrodynamics of heating and evaporation of the target under the action of the electron beam, formation of a pressure pulse, and nonlinear wave processes leading to internal fractures and spalling phenomena in the target unevaporated material. We used wide-range equation of state (semi-empirical QEOS model) [4] for the description of the liquid and solid phases of matter at low temperatures. The wave processes in a solid material can also be calculated in the approximation of a barotropic medium; in this case, we accept the equation of state in the form of Mie-Grüneisen or Tait. To identify the destruction zones, the criterion of the highest principal stress was used, taking into account the formation of a crack in a single-shore model and the criterion for the accumulation of fatigue damage according to the Tuler-Bucher model.

The simulation reproduced the formation of elastic waves in the target. The dynamics of the wave front represented in the Fig.2 is in good agreement with the data of the laser shadow chronogram. Here the left column is the computed density distributions in the plane of symmetry of the target (the irradiated surface is $z = 0$). And the right column shows appropriate shadowgram profiles in the same time points. Fig.3 shows the destruction area in the target. One can see that the wave processes in the target are essentially non-one-dimensional.

The speed of the wave front, obtained in the calculation is $v = 3.25$ km/s, which is slightly less than the experimental value. The calculated density and pressure distributions (see Fig.4) also clearly show the formation of the second (starting from $t \sim 1$ μs) and the third (starting from $t \sim 3$ μs) compression waves and the tension region at the target axis, where, starting from $t \sim 5$ μs, internal destruction of the material occurs. The speed of the front of the second compression wave is less than that of the first one, $v_2 = 3$ km/s. Similar wave pattern was observed in experiments [1] for Plexiglas.

The article [1] presents experimental results and theoretical estimates for two targets made of Plexiglas and K8 glass. The main parameters of Plexiglas experiments were the following: the maximum value of the electron beam current $I = 44$ kA, the average voltage value $U = 230$ kV, the electron pulse width at half maximum $\tau_{1/2} = 150$ ns, the beam energy $W = 980$ J. This is rather close to the conditions of our experiment with epoxy resin. The physical constants for epoxy resin are also close in value to those for Plexiglas as listed in Table 1.

Table 1. The physical properties of the materials

Material	**Volumetric sound speed V_b, km/s**	**Poisson ratio ν**	**Young's modulus E, 10^{10} Pa**	**Normal refractive index n_0**	**Normal density ρ_0, g/cm^3**
Plexiglas	2.2	0.34	0.35	1.48	1.18
Epoxy	2.26	0.42	0.4	1.55	1.18

Velocity of the compression wave front v and the maximum pressure at the compression wave front P_{max} for Plexiglas were estimated in [1] using laser shadow chronogram. The parameters obtained in the calculation for epoxy resin are comparable with the experimental results for Plexiglas, see Table 2.

Table 2. Parameters of the compression wave

Material	**v, km/s**	**P_{max}, GPa**
Plexiglas (experiment [1])	3.8	2.8
Epoxy (simulation)	3.25	4.8

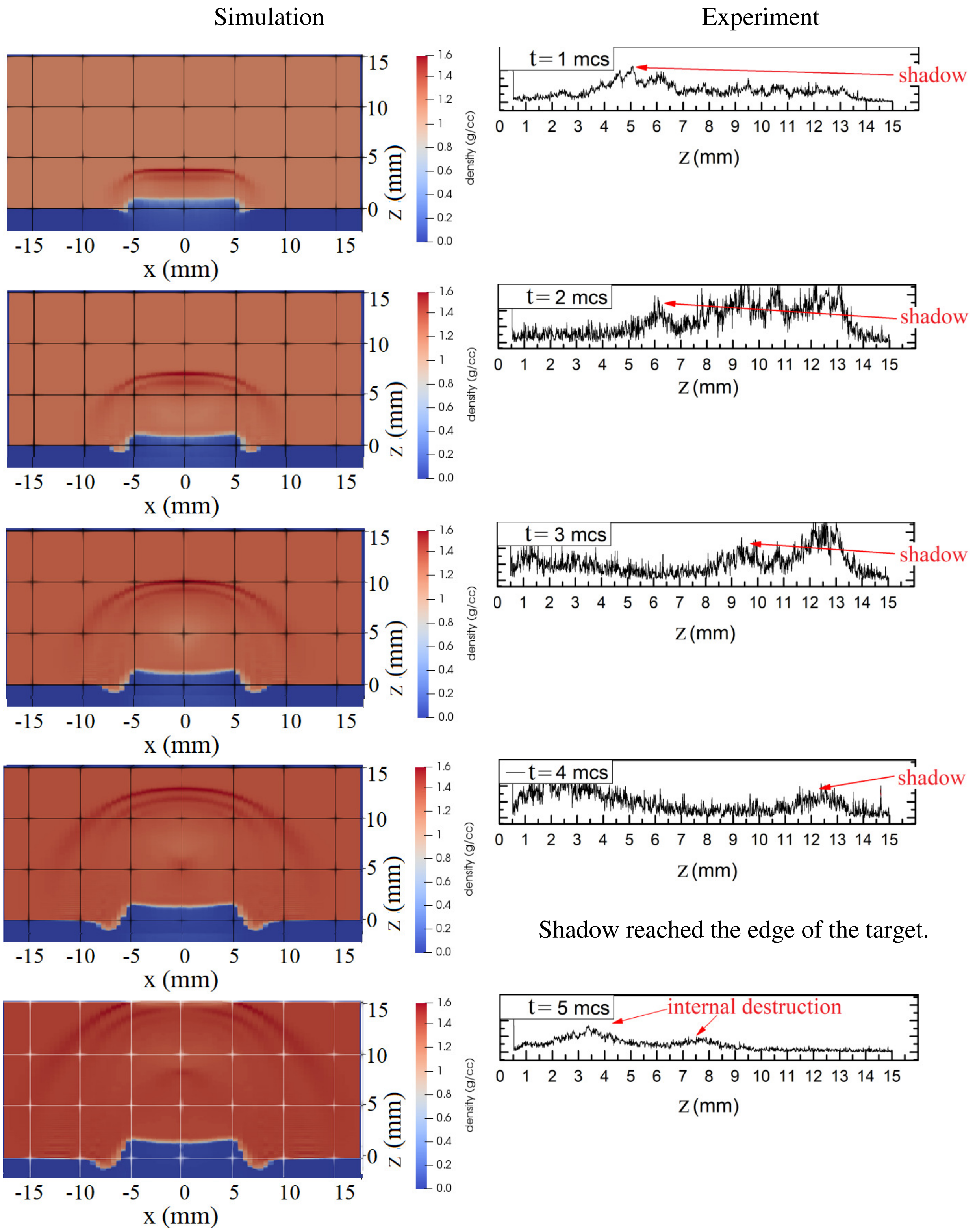

Fig.2. Comparison of the computed density in the target and the shadowgram profiles.

The dark areas at the shadowgram correspond to the deviation of the density of the material from the normal value by $\delta\rho > \delta\rho_{lim}$, which is determined by the allowed deviation of the refractive index *n* [1]. As the probe laser beam was directed along the *X* axis, density deviation in any part of the target at the given height *z* produced a dark point at this *z*.

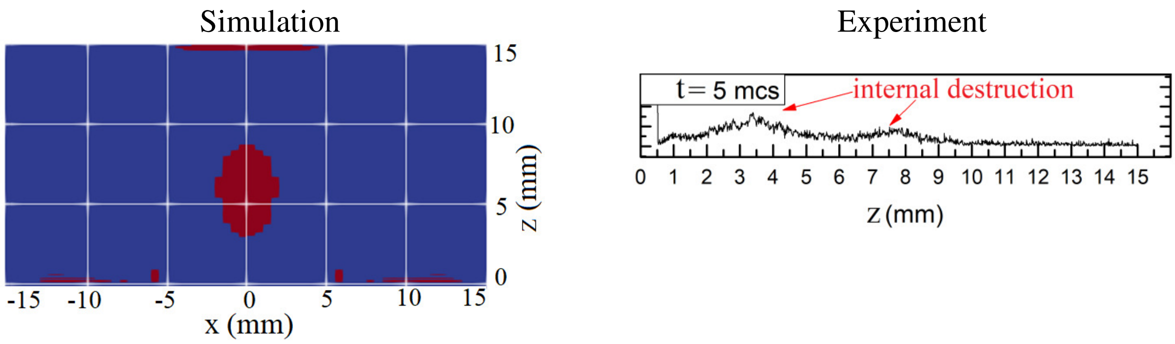

Fig.3. Internal destruction area (red).

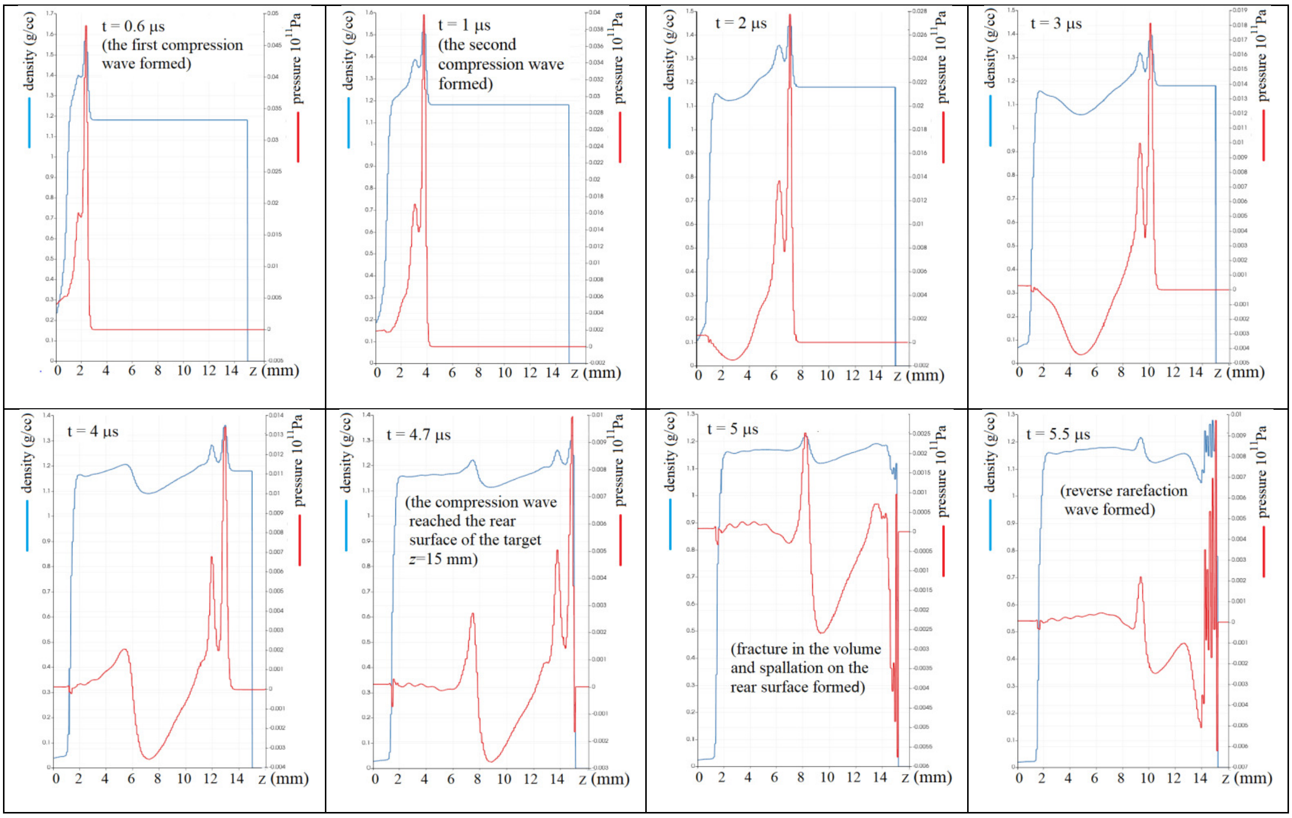

Fig.4. Simulation results. Density and pressure distribution along the target axis.

4. Conclusion

We have investigated a sample of epoxy resin exposed to 600 J/cm^2 REB. Laser shadow chronogram allowed observation of the wave processes in the material and estimation of the compression wave parameters. The wave pattern in epoxy resin appeared to be comparable but not identical with that obtained for Plexiglas. Brittle fracture in the volume of the target and spallation on its rear surface took place.

End-to-end computer model was developed to support these experiments. The model included the action of the REB on the target front surface resulted in the evaporation of the substance and formation of a pressure pulse, gasdynamic phenomena in the diode gap, and elastoplastic phenomena in the solid target, leading to destruction in the unevaporated matter. Wave processes in a target are essentially non-one-dimensional, and require 3D simulation in the case of non-cylinder sample. Appropriate modeling of this complex multiphysics problem is based on high resolution numerical methods as well as on high performance computing. The implemented computer models are verified by experimental data. Comparison of simulation results with experimental data is used to test the applied models of volumetric fractures and spallations in brittle solids, and to validate wide-range equations of state. The developed software can be used for numerical stress-strain analysis of various structural units loaded by strong pulsed forces and/or energy fluxes.

Acknowledgement

The calculations were performed on the hybrid supercomputer K60 installed in the Supercomputer Centre of Collective Usage of KIAM RAS.

5. References

[1] Demidov B.A., Kazakov E.D., Kalinin Y.G., Krutikov D.I., Kurilo A.A. , Orlov M.Yu., Strizhakov M.G., Tkachenko S.I., Chukbar K.V., Shashkov A.Yu., *Instrum. Exp. Tech.*, **63**, 370, 2020; doi: 10.1134/S0020441220030094

[2] Kazakov E.D., Kalinin Y.G., Krutikov D.I., Kurilo A.A., Orlov M.Yu., Strizhakov M.G., Tkachenko S.I., Shashkov A.Yu., *Plasma Phys. Rep.*, **47**, 803, 2021; doi: 10.1134/S1063780X21080067

[3] Boykov D.S., Olkhovskaya O.G., Gasilov V.A., *Math. Models Comput. Simul.*, **14**(4), 599, 2022; doi: 10.1134/S2070048222040044

[4] Software package and database THERMOS [online]; https://www.keldysh.ru/cgi/thermos/navigation.pl?en,home