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Comparative study of the response of plastic materials to the high-current electron beam of the Kalmar facility impact

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Abstract. This paper presents the results of a study of the impact of a high-current electron beam of the Kalmar accelerator with a cutoff electron energy of up to 350 keV on igdantine and low molecular weight nitrile butadiene rubber SKN-18-KTR. The materials are similar in mechanical and physical properties, but differ in chemical structure. It has been shown that, at a beam energy of less than 600 J, the destruction of igdantin begins to a depth significantly exceeding the electron range, while nitrile rubber withstands a load of more than 700 J without significant damage. It is demonstrated that the dynamics of plasma expansion from the surface of igdantin regularly demonstrates specific.
Keywords: high current electron beams, polymers, gels, igdantin, low molecular weight butadiene-nitrile rubber.

1. Introduction

At present, using high-power electron beams, the features of destruction of metals [1, 2], polymers [3, 4], and composite materials [5] have been studied in sufficient detail. However, the behavior of polymer gels, using the example of igdantin, showed an interesting feature – under a powerful electron beam impact with an energy of more than 1 MeV, the decisive role in their destruction is played not by shock-wave, but by radiation-thermal processes [6]. In this regard, the study of such materials is of particular interest from the point of view of searching for threshold values of the input energy for triggering radiation-thermal processes. Also of significant importance is the behavior of the material expanding from the surface, which may indicate both the initiation of these processes and the effect of the plasma closing the diode gap on the degree of destruction of the samples after irradiation.

In this work, we considered the effect of a high-current electron beam from the Kalmar setup on two materials that are similar in mechanical and physical properties, but differ in chemical structure – igdantine and low molecular weight butadiene-nitrile rubber SKN-18-KTR, which has a rare network of chemical bonds between rubber macromolecules formed by quinol ether. Previous experiments on the study of the destruction of polystyrene, PMMA, and epoxy resin at the Kalmar facility showed that even when materials with similar mechanical properties are destroyed by shock-wave mechanisms, the nature of their destruction can differ significantly. Moreover, the internal destruction of PMMA and epoxy resin is quite specific and has been reproduced by mathematical modeling only in recent years [7, 8]. Also, calculations were made of the effect of the electron beam of the Kalmar setup on the sample materials by the Monte Carlo method. Estimates of absorbed doses in the thickness of the material have been carried out.

2. Experimental setup

Sample irradiation experiments were carried out on a Kalmar high-current electron accelerator, the main element of which is a double forming line, from which a short voltage pulse is transmitted to a vacuum diode. The beam current is formed due to explosive emission from the cathode. The irradiated samples are placed on an anode plate with a hole that ensures that the electron beam hits them and are pressed against the anode surface by a Plexiglas plate. In these experiments, the diode voltage was 300 kV, and the current varied in the range of 20–30 kA. The diode current was measured by a low-inductance shunt, and the voltage was determined from the readings of a capacitive divider installed in front of the diode input. An X-ray pinhole camera was used to determine the size of the region of interaction between the beam and the target. Also, the plasma dynamics in the diode gap was studied by the method of laser shadow photography with streak-camera registration [9]. Image synchronization was implemented by registering an image of an LED triggered by a pulse from a current-measuring shunt. The scheme of the experiment is shown in Fig.1.

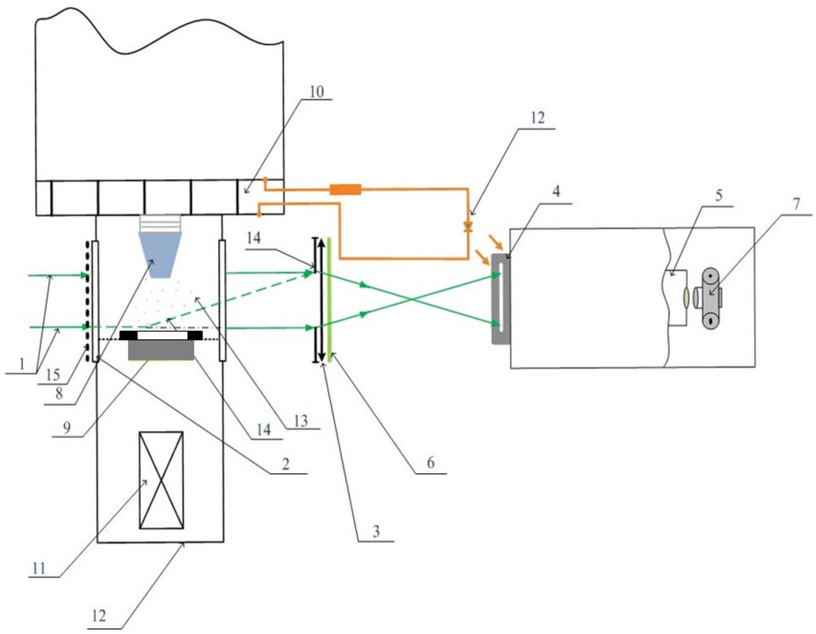

Fig.1. Scheme of the experiment. 1 – laser beam, 2 – viewing window, 3 – objective, 4 – slit of the electron-optical camera, 5 – streak-camera, 6 – filter, 7 – camera, 8 – cathode, 9 – sample, 10 – shunt, 11 – pinhole camera, 12 – LED, 13 – vacuum diode gap, 14 – diaphragm, 15 – calibration grating.

3. Experimental results and calculations

At the first stage, experiments were carried out on the irradiation of igdantin samples at various beam energies. A typical dependence electron beam power from time is shown in Fig.2.

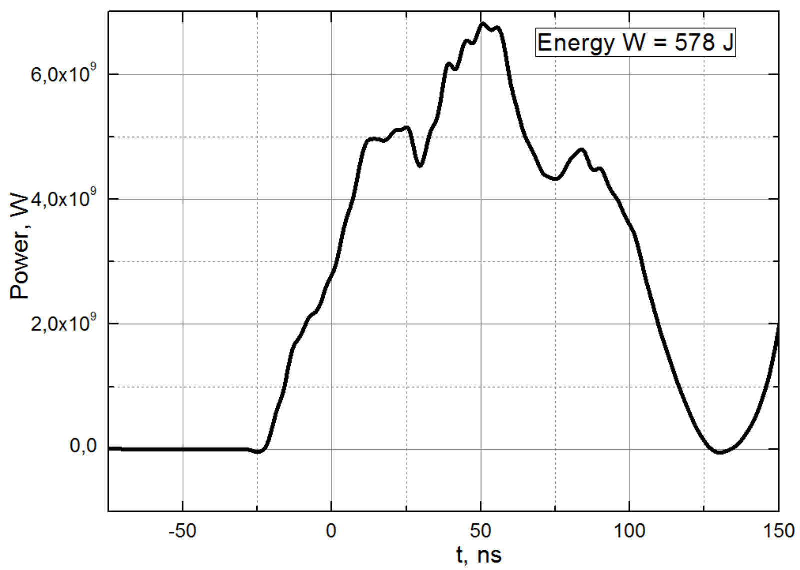

Fig.2. Typical electron beam power of the Kalmar setup.

Fig.3 and Fig.4 show two irradiated samples. The area affected by the beam was quite clearly printed on the samples, which is also confirmed by pinhole camera frames. It can be seen that on the right target, the electron beam provided the conditions for triggering radiation-thermal processes, since the depth of the hole significantly exceeds the range of electrons in the material. This demonstrates the presence of a threshold effect for triggering such processes. Since the energy inside the beam has a Gaussian distribution over the area, the threshold is overcome only on the beam axis, in contrast to the experiments carried out on the RS-20 facility [5], where the average energy per pulse is much higher. The mass loss in this case was 185 mg.

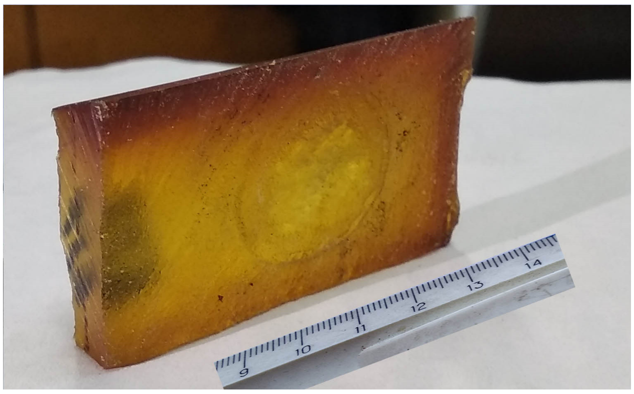

Fig.3. An irradiated sample of igdantin. Beam energy 430 J.

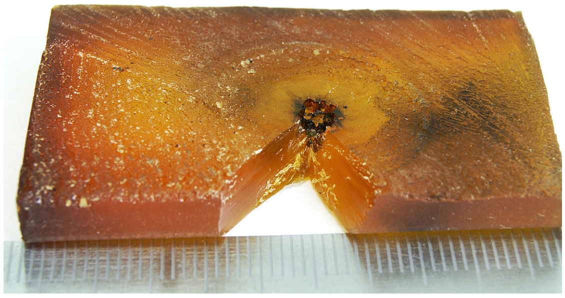

Fig.4. An irradiated sample of igdantin. Beam energy 580 J.

From Fig.5, which shows the central region of the damaged target, it can be seen that the threshold effect is preceded by a process that results in “smoothing” of the sample surface at lower energy densities. The same phenomenon was observed in the central region of the sample in Fig.3.

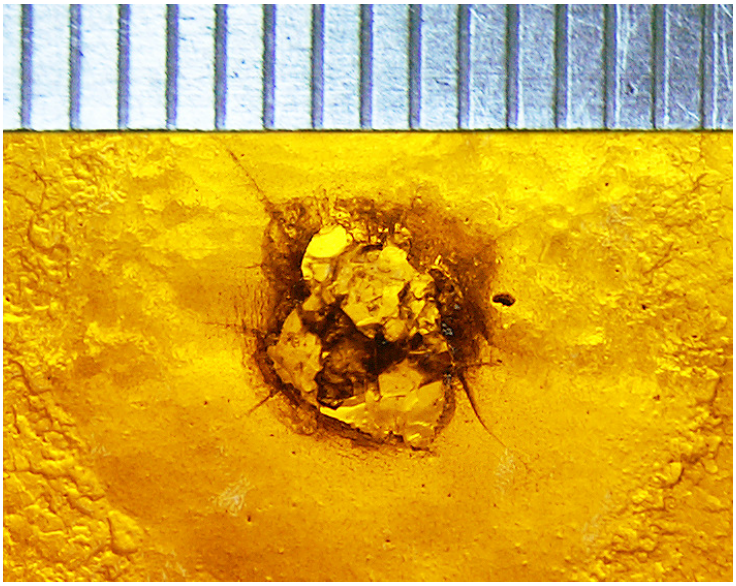

Fig.5. Damaged area of the igdantin sample.

In the experiment with a higher beam energy, anomalous plasma behavior was also observed, accompanied by pinching of a low-density plasma column or breakdown in the resulting plasma diode, as shown in Fig.6. Such an effect was observed earlier on epoxy resin and some composite materials. This is probably due to the fast filling of the diode gap with light fractions of low density, which cannot be observed by this method.

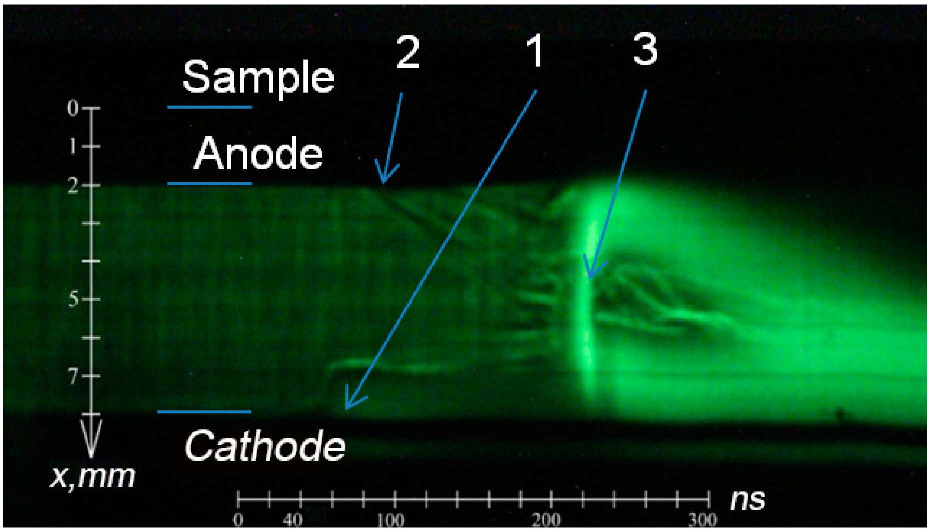

Fig.6. Streak-camera image of plasma dynamics on the axis of a plasma diode in a laser shadow.

The visible expansion of the anode plasma (2) begins with some delay relative to the cathode plasma (1) due to the fact that 2 mm of space is shaded by the anode plate. Typical anode and cathode plasma velocity is ~ 10 km/s. And even before the gap is bridged, we observe a powerful flash (3) of the plasma's own glow, propagating from the center of the diode to the anode and cathode at a speed of more than 100 km/s.

At the same time, upon irradiation of butadiene-nitrile rubber, samples of which are shown in Fig.7 and Fig.8, only a transient process is observed, leading to smoothing of the central part of the region of interaction of the beam with the target, even at a beam energy of 740 J. In this case, the mass loss was also quite significant – 162 mg, while at a beam energy of 350 J – 100 mg.

Fig.7. Irradiated rubber sample. Beam energy 350 J.

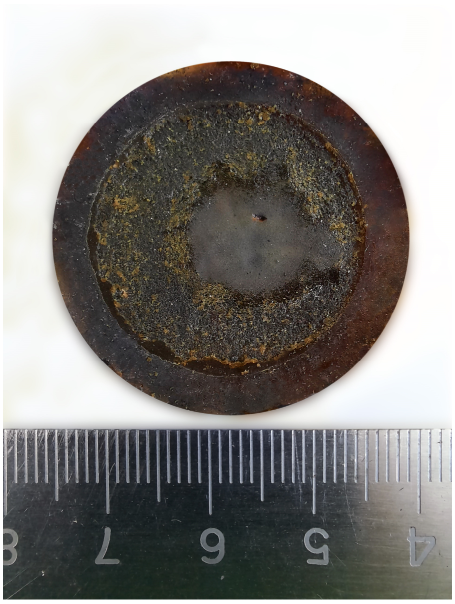

Fig.8. Irradiated rubber sample. Beam energy 740 J.

Also, calculations were made of the parameters of the impact of high-current electron beams of the Kalmar accelerator on SKN-10 KT samples and estimates of the propagation of the relativistic electron beam given in Tables 1–2 and the distribution of the absorbed dose over the thickness of the samples from all particles of the source (Fig.9).

Table 1. Parameters of the impact of relativistic electron beams from the Kalmar accelerator on SKN-10 KTR samples

Experiment	E_{eb}, J	W_{max}, GW	S_{eq}, cm^2	I_A, kA	<E>, keV	τ_0, ns
28.10.21	350	3.97	0.785	16.1	200	112
29.10.21	740	7.76	0.283	25.2	184	154

Table 2. Estimates of the propagation of the relativistic electron beam in our experiments

Experiment	H_e, µm	H_{1000K}, µm	D_{max}, MGy	H_{Dmax}, µm	D_{abs}, MGy	<D_{abs}>, MGy	I_m, Pa·s	P, GPa
28.10.21	758	565	12.0	12	8.6	7.47	1331	6.47
29.10.21	912	805	80.1	162	80.1	33.1	3842	60.2

The following designations are used in the tables: E_{eb} – electron beam energy incident on the sample surface, W_{max} – maximum electron beam power, S_{eq} – irradiation area corresponding to almost uniform current of the electron beam (in the range of 15%), I_A – electron beam current amplitude corresponding to the area S_{eq}, <E> – average electron energy, τ_0 – duration of irradiation at half-height of the amplitude value of the current, H_e – depth of electron path (attenuation by 3 orders of magnitude), H_{1000K} – depth at which a temperature of 1000 K is reached, D_{max} – maximum value of the absorbed dose, H_{Dmax} – depth at which the maximum value of the absorbed dose is reached, D_{abs} – absorbed dose on the sample surface, <D_{abs}> – absorbed dose averaged at the beam half-path depth, I_m – mechanical pressure impulse, P – pressure.

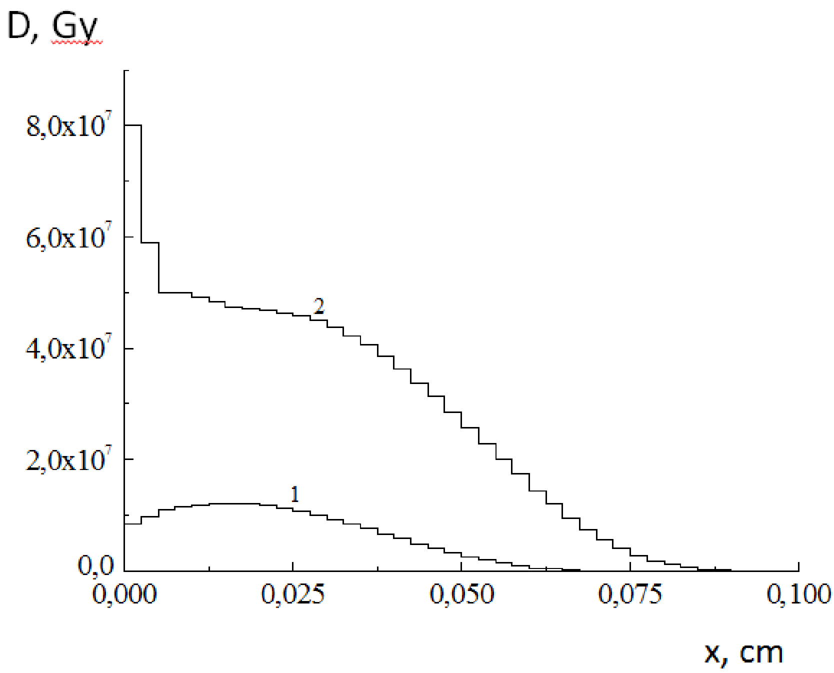

Fig.9. Distribution of the absorbed dose over the thickness of the samples from all particles of the source.

Considering that the density of igdantin is close to the density of rubber, it can be considered within the error that the obtained data clearly demonstrate the appearance of transient and threshold effects. It should be noted that with a more powerful impact, the weight loss from the rubber sample was about 160 mg, while at a beam energy of 350 J it was about 100 mg.

Also, a microscopic study of samples of butadiene-nitrile rubber was carried out, which clearly demonstrated the boundaries of the transition. Fig.10 and fig.11 show the boundary of the irradiation area.

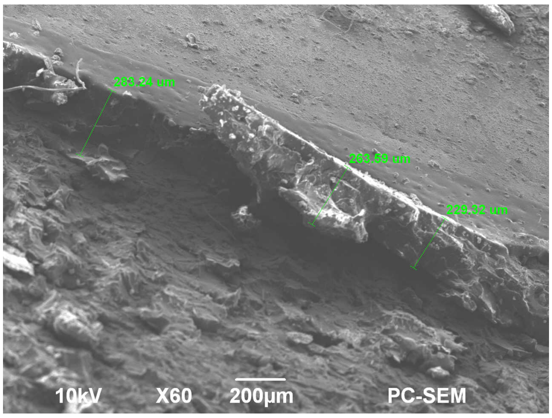

Fig.10. Boundary of the irradiation area.
Beam energy 350 J.

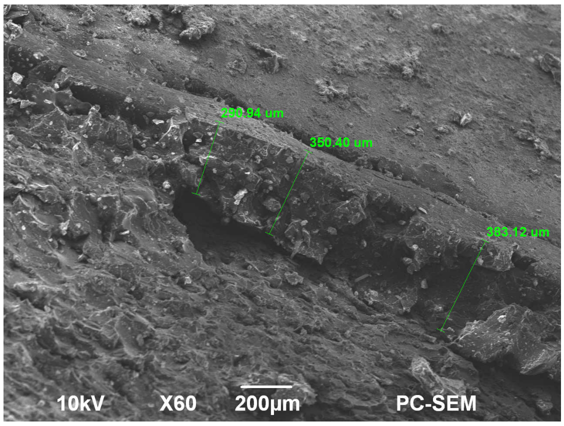

Fig.11. Boundary of the irradiation area.
Beam energy 740 J.

The appearance of the boundary and the rough surface is similar for both samples. Of greatest interest is the transition between smooth and rough surfaces (Fig. 12) for the sample irradiated at an energy of 740 J. The smooth surface (Fig. 13) has a complex bubble internal structure, as if melted.

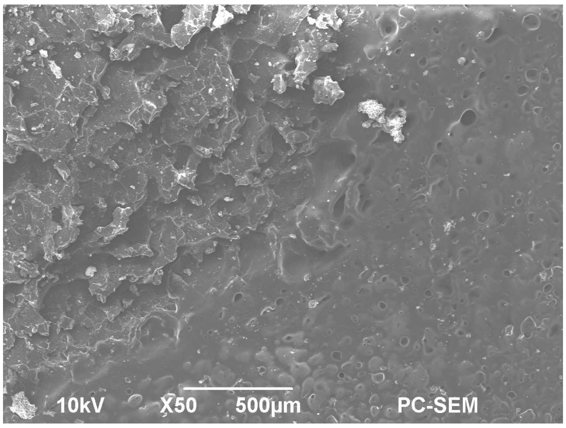

Fig.12. Boundary of the smooth and rough surfaces.
Beam energy 740 J.

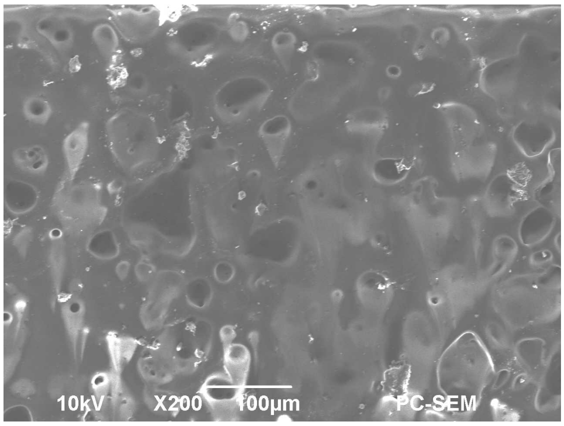

Fig.13. Smooth surface.
Beam energy 740 J.

4. Conclusion

A comparative study of the response of igdantin and low-molecular-weight nitrile butadiene rubber to the action of a high-current electron beam with an energy of 350 to 740 J was carried out. It was shown that the destruction of such materials due to radiation-thermal processes has a threshold character with a transition phase. At threshold values of the energy density, the depth of destruction of the sample significantly exceeds the depth of the electron path, which is confirmed by the calculations performed.

It is shown that the destruction of igdantin due to radiation-thermal processes occurs at a beam energy of 580 J, while in nitrile rubber, even at 740 J, only a transition phase is observed. It has also been demonstrated that radiation-thermal destruction is accompanied by specific behavior of the plasma in the diode gap of the accelerator, which, apparently, is due to the rapid filling with light fractions from the sample.

5. References

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