Processes of failure of polymethyl methacrylate under high-velocity impact loading and pulse laser treatment


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SUMMARY

An investigation was made of the effect of high-velocity impact loading and laser irradiation on processes of failure in polymethyl methacrylate. Under impact load, PMMA fails, with the formation of cracks and the release of large fragments. In the case of laser treatment of a PMMA target, loss of continuity of the target material occurs mainly in the near-surface regions – front and back. The maximum fractures are observed on the back surface of the target. The conducted investigations showed that, for polymethyl methacrylate, there exist differences for the different forms of treatment.

Processes of pulse treatment of solid targets are accompanied with the formation of compressive pulses (shock waves) in the target material, which, reflecting from free surfaces, cause the appearance of discharge waves capable, at sufficient amplitude of the tensile stresses and duration of their action, of causing loss of continuity of the target material [1, 2]. Fractures of this type are called spall fractures. The task of this work is a detailed examination of processes of failure in polymethyl methacrylate (PMMA) with different forms of dynamic loading. Obtaining experimental data on the dynamic strength of PMMA is central to solving many problems.

Under impact load, PMMA fails with the formation of cracks and the release of large fragments. For impact velocities of 1.5–2.5 km/s with a polyethylene striker, in the PMMA target the formation of a large axisymmetrical central fragment was recorded. In the case of non-escape of the central fragment, abnormal craters are produced in the PMMA with a central protuberance and a ring-shaped hollow, which can be attributed to insufficient intensity and duration of the tensile stresses.

The conducted numerical calculation made it possible to indicate the time of the start of the process of failure \( t = 4 \, \mu \text{s} \). On this basis, it can be asserted that tensile stresses appear immediately as the compressive wave and the discharge waves from the front surface advance deep into the target, long before their reflection from the back surface.

On the contact surface, and in a certain volume adjacent to it, failure of the specimen as a whole does not occur. Here, stresses bearing the nature of isostatic compression develop in these regions. The formation of cracks and the loss of continuity occur where fairly large tensile and shear stresses develop. From the above it follows that, in PMMA, craters are formed by brittle failure, the formation of cracks, and the release of substance in the form of fragments. Crater formation in PMMA is caused by front spall.

On the free front surface, the pressure is zero, as in the reflected wave there arises a stress equal in magnitude but opposite in sign to the incident wave. The incident wave is the wave of elongation. The result of adding these waves leads to the development, in certain regions deep in the target for a certain time, of tensile stresses exceeding the tensile strength of the material, and a crack arises, and then spall. As the intensity of the waves falls, fracture ceases.

In the case of laser treatment of a PMMA target, loss of continuity of the target material occurs mainly in the near-surface regions – front and back. The maximum fractures are observed at the back surface of the target.
Such a pattern of development of degradative processes is characteristic with the given method of pulse treatment.

The main difference qualitatively changing the pattern of action of the laser pulse by comparison with impact loading is the absence of front spall, which is determined by the absence of a zone of tensile stresses (axial and radial) at a certain depth from the front surface. The seats of fractures present in the case of laser treatment directly adjoin the front surface and are positioned along the axis practically through the entire thickness of the target.

Another important difference in the results obtained in the case of laser irradiation is the presence of a back spall, which was absent in experiments in impact loading. This makes it possible to conclude that the use of laser pulses is more effective for the creation of conditions for spall failure and carrying out investigations in this region [3].

The conducted investigations make it possible to conclude that, for polymethyl methacrylate, differences exist for the different types of treatment.

Kostin et al. [4] showed that the dimensionless magnitude $h/D$ of the craters formed in targets under the impact of macroparticles with velocities of $2–10$ km/s reduces for different materials to a single dependence on the parameter $x = \rho V_0^2/\rho_0$, km$^2$/s$^2$. Therefore, for our calculations, dependences of $h/D$ on this variable $x$ were plotted (Figure 1).

Line 1 in Figure 1 corresponds to the equation:

$$h/D = 0.86x_1$$

and was obtained by the least-squares method with generalisation of all experiments [5] conducted for a PE striker and a PMMA target.

We calculated the dependence of $h/D$ on the energy of the laser pulse (Table 1).

From the data in Table 1, lines 2 and 3 in Figure 1 for the case of pulse laser treatment were obtained.

Line 2 corresponds to the equation:

$$h/D = 2.2x_2$$

Line 3 is described by the relationship:

$$h/D = 0.45x_3$$

Comparison of the data presented in Figure 1 and equations (1), (2), and (3) indicates that the mechanisms of failure of PMMA under high-velocity impact loading and pulse laser treatment with identical energies of loading differ strongly. If the $x$ coefficients on dependences 2 and 3 up to striker energies $E = 5 \times 10^3$ J are compared, then $x_2$ is 2.56-fold greater than $x_1$, and 4.8-fold greater than $x_3$.

Analysis of the dependences 2 and 3 indicates that, under pulse laser treatment, the rate of growth in the depth of penetration is almost threefold greater at the start of treatment by comparison with high-velocity impact loading, and then slows down more than fourfold (line 3). Subsequent analysis of the pattern of failure of PMMA under pulse laser treatment showed that the channels formed by the laser pulse collapse as they move deep into the target. Close to the channels, regions of intense plastic flow with a highly disperse structure are formed. The positions of lines 2 and 3 in Figure 1 and the ratio of $x_2$ and $x_3$ correspond to brittle failure beginning and developing at the very start (up to 6 µs) of pulse laser treatment, which is converted into plastic failure of the target material in regions located along the axis of the specimen over the entire depth of the target in a radius of 1 cm.

Such a mechanism of failure of PMMA in the case of pulse laser treatment explains the absence of zones of axial and radial tensile stresses at a depth of only 0.5 cm from the front surface of the target, and also the appearance of back spall, which was absent in experiments and calculations of high-velocity impact loading [5, 6].

Table 1. The dependence of $h/D$ on the energy of the laser pulse

<table>
<thead>
<tr>
<th>$E \times 10^3$, J</th>
<th>0.50</th>
<th>1.27</th>
<th>2.49</th>
<th>3.97</th>
<th>7.38</th>
<th>11.23</th>
<th>13.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h/D$ (impact)</td>
<td>0.33</td>
<td>0.44</td>
<td>0.47</td>
<td>0.55</td>
<td>0.83</td>
<td>1.22</td>
<td>1.25</td>
</tr>
<tr>
<td>$h/D$ (laser)</td>
<td>0.62</td>
<td>0.88</td>
<td>1.16</td>
<td>1.25</td>
<td>1.57</td>
<td>1.60</td>
<td>1.72</td>
</tr>
</tbody>
</table>

Figure 1. The dependences of the dimensionless depth of penetration of a PE striker (line 1) and a laser pulse front (lines 2 and 3) into a PMMA target on parameter x.
CONCLUSIONS

From the analysis above it can be concluded that the use of laser pulses is more effective for the creation of conditions for spall failure than the use of high-velocity impact loading. Although it was assumed that the general scheme of development of hydrodynamic processes remains the same in the two cases, the mechanisms of crater formation and failure under these pulse effects differ greatly.

Comparison of the results of failure under high-velocity impact loading and laser treatment gives grounds for saying that the laser pulse acts more destructively than impact loading, as in this case the region of fractures occupies a greater volume.

REFERENCES
