Modeling of micrometeoritic streams under the action of the high-power laser pulse on multicomponent polycrystal rocks

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Abstract. The paper presents the analysis of interaction of the high-power laser pulse with multicomponent polycrystal rocks. Experiments were completed on a laser facility “Saturn” with intensity of $10^{10}$–$10^{13}$ W/cm$^2$. Structural analysis of the materials from the spall crater and from the plasma flame show significant differences. The article demonstrates experimental results of the spall formation moment depending on the thickness of the radiated target. The scale of damage to aluminium 6 µm thick foil at the rare side of the target is illustrated when it is hit by the andesite fragments from a spall crater.

1. Introduction
Today, due to LTS program research, laser radiation interaction with metals and dielectrics is well studied in a wide range of intensities. However, the mechanism of laser radiation interaction with multicomponent polycrystalline rocks at $I \sim 10^{10}$–$10^{13}$ W/cm$^2$ is studied insufficiently and poorly described in literature.

It is of great interest for a variety of technological applications, in particular, for laser simulation of micrometeorite impact. There were a number of articles in scientific literature on laser simulation of micrometeorite impact with the help of metallic foils acceleration [1]. Though it was known that most of micrometeorites are particles of stony dust [2], the information about laser simulation of micrometeorite impact was poorly described in literature.

The problem of laser simulation of corresponding micrometeorite impacts is therefore considered to be studied thoroughly. Andesite can be used as the main material. Its composition is close to that of meteorites and Martian dust [3].

Taking these facts into consideration, the aim of this research was the detailed study of the high-power laser radiation interaction with the multicomponent polycrystalline rocks and the development of a laser-plasma source of µm-sized particles with solid density with the speed close to that in the micrometeorite flows.

2. Experimental results
The experiments were carried out at the high-power facility “Saturn” described in detail in [4]. Laser pulse was formed at the output of the final amplifier with the energy $E_L \sim 20$–50 J, FWHM duration $\tau_{FWHM} \approx 30$ ns and divergence $\theta \sim 1.5 \cdot 10^{-4}$ rad. Focal spot diameter $D_L$ varied from 100 µm to 300 µm.

The research of the crater formation process requires accurate parameters of the plasma flame and the magnitude of the ablation pressure, generating a shock wave in the unevaporated part of the target.

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A simplified analytical model of a stationary spherical expansion of plasma, proposed by P. Mora [5], was used to calculate the flame parameters. It is supposed that the main mechanism of laser radiation is the inverse bremsstrahlung.

It should be pointed out that the plasma flame temperature can be used as a parameter for model verification. The method of absorbers (filters) was used to determine the temperature of the resulting dense plasma. As the test objects for verification method, Al targets were used.

The data obtained for aluminium and andesite targets [6] agree within the experimental error with the results calculated on the basis of Mora’s plasma expansion model [5]. It is shown that Mora’s model can be used to obtain reliable data on the plasma ablation pressure and temperature. Theoretical calculations according to Mora’s model show ablation pressure of about 4 Mbar for laser radiation intensity $I = 10^{13}$ W/cm$^2$.

Crater parameters in the studied range of intensity can be described by means of an analytical model suggested by S. Yu. Guskov [7]. Crater formation during the laser interaction with the target is the result of phase transformations of pressed and heated substance behind the shock wave front.

The calculation results [4] have demonstrated that the estimated crater’s diameter and depth for aluminum and andesite targets agree with the experimental data. The model allows to estimate the shock wave speed. According to the experiments with 2 cm thick andesite targets, the shock wave speed is about 5 km/s and it decreases before coming to free surface [4].

To study the shock wave exit onto the rear side, series of shootings at thin andesite [8] targets were made. As a result of all our experiments with thin targets, the spall crater was formed from rear side of the targets. In some cases, a through channel was formed inside the spall crater. As a rule, it was formed on the targets with thickness less than 350 µm.

To study the material ejected from the plasma flame and the spall crater, targets material spraying on special silicon plates was researched [4]. The analysis of spraying structure is carried out with the help of the electron microscope, whereas chemical analysis is studied using the X-ray spectrometer.

There is a large number of liquid fragments in the material ejected from the crater into the front space (figure 1). At the same time, there are only solid fragments (figure 2) in the material ejected from the spall. This fact proves that the temperature of the material from the spall crater is lower than the melting temperature. Sizes of the fragments vary from 0.5 µm to 50 µm [8].

**Figure 1.** Electron photographs of the andesite condensate film in the front space of the target $D_L = 100$ µm, $I = 5 \cdot 10^{12}$ W/cm$^2$.

**Figure 2.** Electron photographs of the andesite condensate film from the rear side of the target $D_L = 100$ µm, $I = 5 \cdot 10^{12}$ W/cm$^2$. 
To study the moment of spall formation in thin targets, the scheme presented in figure 3 was developed. A thin stripe of 6 µm thick Al foil is placed into the base holes and is adjusted by contacts C1 and C2. The target is fixed on the base close to the stripe.

When the foil is being torn, the oscilloscope records potential shift. The moment of diode D1 switching on is synchronized with the laser impulse input on the front surface of the target.

Figure 4 shows signals registered at Al foil tearing during irradiation of 400 µm thick andesite targets. The signal of the foil tearing on one of the targets is shown with negative magnitude for better visualization. One should note satisfactory repeatability of the results obtained at the same thickness of the target and at the same laser intensity.

Figure 5 shows the dependence of the spall formation moment on the thickness of andesite targets. The spall is formed at shock wave ejection on the free surface of the target and depression wave generation. Prior to the moment of spall formation, the shock wave passes a distance of about a target thickness. The speed of the shock wave for targets with thicknesses from 400 to 700 µm is \( W \approx 7 \) km/s. This data interpretation is coherent with the calculation data [4]. Taking in consideration the material speed doubling at shock wave ejection on the free surface and approximation of a strong shock wave, expansion velocity of fragments from the spall crater is proved to be around \( 4W/(\gamma+1) \sim 10 \) km/s.
If the thickness of the target is getting less than 400 µm, a through channel can be formed in the spall crater. The glow at the rare side of the target was registered during the experiments with a through channel formation [8].

To show the scale of surface damage when andesite fragments from the spall crater hit it, a piece of 6 µm thick aluminum foil was fixed 2 mm and 6 mm off the rare side of the target. In figure 6 one can see the traces of the damage to foil induced by the fragments. The sizes of the craters in foil vary from 1–20 µm (left in figure 6) to 2 mm (right in figure 6).

3. Conclusion

Thus, it has been demonstrated that under the action of the laser pulse of moderate intensity on the multicomponent polycrystal rocks, µm-sized fragments are formed at the rare sides of targets. These fragments are equivalent in composition, temperature, dimension, and speed to the micrometeorite flows in space.

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