COMPUTATION OF BLAST WAVE ENERGY IN LIBS USING SHADOWGRAPHY

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1. INTRODUCTION

Shadowgraphy is an optical method, that can be used to observe non-uniformities in transparent media, such as air or water. In connection with Laser-Induced Breakdown Spectroscopy (LIBS) we can see blast wave, that was created by ablation of a sample.

This method in LIBS can be used for observation of different ablation and expansion mechanism using ns, fs or ps laser pulse [Zeng 2005], impact of the wavelength of the ablation laser [Boueri 2009] or its energy fluence [Rezaei 2014]. It is also possible to use Shadowgraphy to see impact on the behaviour of the blast wave expansion in different ambient gas at certain pressure [Skrodzki 2016], or even for underwater ablation [Sakka 2009].

Several models were created for the blast wave expansion, that can predict its distance from the samples surface, or even initial energy of the blast wave. Examples of these models are Drag, Sedov-Taylor and Jones model [Harilal 2003, Taylor 1950]. In our research we focused on using Sedov-Taylor and Jones model in order to calculate initial energy of the blast wave. This way we can approximately determine amount of energy used for ablation of the materials.

2. EXPERIMENTAL

In our experiments we used four different samples: steel, glass, bronze and soft tissues. Shadowgraphy images were captured for these samples in time interval between 100 ns and 10 μs after the ablation. Window between two consecutive times is 50 ns up to 1500 ns after the ablation, and 100 ns up to 10 μs. Finer time resolution in the earlier stage of the expansion is selected due to the Sedov-Taylor model. For each time after the ablation five laser pulses were shot into one spot, creating five shadowgraphy images. Radius of the blast wave was measured as distance from the centre of the ablation to the outer edge of the blast wave, and then averaged. For another time after the ablation new spot on the sample was selected. This way, shadowgraphy was observed for 7, 13, 19, 25, 32, 36, 44 and 50 mJ of the laser energy.

3. RESULTS AND DISCUSSION

3.1. Sedov-Taylor model

Sedov-Taylor model describes relation between distance of the shock wave from the samples surface *r* in time *t* from the ablation [Zel'dovich 1966]:

$$r = \zeta_0 \frac{E_0^{\frac{1}{\beta+2}}}{\rho_1} t^{\frac{2}{\beta+2}} \approx A\, t^{\frac{2}{5}}, \tag{1}$$

where ζ_0 is a constant approximately equal to unity, E_0 is initial energy of the blast wave, ρ_1 is the mass density of the undisturbed ambient gas, t is time of propagation for the shock wave front after the ablation and β is coefficient related to character of the explosion (β = 1 for planar propagation, β = 2 for cylindrical propagation and β = 3 for spherical propagation).

Example of the shadowgraphy images are displayed in **Figure 1**. By measuring the size of the blast wave, we can observe distance of the blast wave from the centre of the ablation in time. Measured data were used for computation of Sedov-Taylor model from the eq. (*1*), where results are affected by selected time interval.

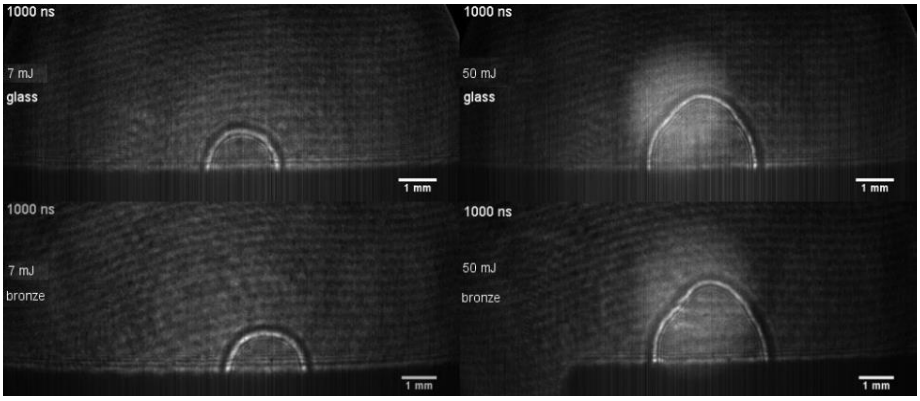

Figure 1. Shadowgraphy for glass and bronze samples ablated with 7 and 50 mJ impulses.

From our data, we can see that Sedov model can provide close representation of the actual data in the earlier stages of the expansion. Since this model is also connected to the initial energy of the blast wave by:

$$E_0 = A^5 * \rho_1 \tag{2}$$

we can use Sedov-Taylor model from the initial stage of the expansion for calculation of this energy. Based on this model, we were able to compute energy conversion coefficient as ratio of laser energy and E_0, as well as difference of these two energies, that represents amount of energy spent on the ablation.

3.2. Jones model

Jones model is also connected with the E_0, therefore we used it for confirmation of our results. This model represents relation between time and blast wave radius as:

$$t = \frac{R_C}{c_0}\left(\frac{2}{5}\right)^{\frac{2}{3}}\left[\left(1+\left(\frac{5}{2}\right)^{\frac{5}{3}}\left(\frac{R}{R_C}\right)^{\frac{5}{2}}\right)^{\frac{5}{2}} - 1\right] \tag{3}$$

where c_0 is speed of sound in the ambient gas and R_C is characteristic radius expressed as:

$$R_C = \left(\lambda_S^5 \frac{E_0}{\gamma p_0}\right)^{\frac{1}{3}} \tag{4}$$

where $\lambda_S{}^5$ is a geometry dependent coefficient, E_0 is shock wave energy, γ is the adiabatic index of the ambient gas and p_0 is its pressure. After fitting measured data with Jones model shown in the eq. (3) we can obtain R_c. Knowing rest of the parameters in eq. (4), we can calculate E_0 for each sample. This result was then compared with Sedov's calculation.

4. Conclusions

In this work we have shown that Sedov-Taylor model can be used for blast wave energy computation. This can also determine energy that was spent for the ablation. From our data it is clear, that this model can be used only in the earlier stages of the blast wave expansion. Moreover, we used Jones model for confirmation of our results. However, this model is a bit more complicated and has a more demanding computation.

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