DOI 10.1007/s11182-017-0933-x

*Russian Physics Journal, Vol. 59, No. 9, January, 2017 (Russian Original No. 9, September, 2016)*

# QUANTUM ELECTRONICS

## DYNAMICS OF CRATER EVOLUTION DURING LASER TREATMENT OF MATERIALS

**S. V. Vasilijev,[1] N. V. Zharkii,[1] A. Yu. Ivanov,[1] A. V. Kopytskii,[2] and V. I. Nedolugov[1]**

UDC 535.391: 621.376

*Acoustic emission of the destruction zone formed upon exposure of the metal surface to pulsed laser radiation is considered. A dependence of the waveform and spectrum of acoustic vibrations on the parameters of the irradiated material and a law of increase in the crater depth are determined. It is revealed that for the copper sample surface irradiated by the laser pulse with duration of ~20 μs, the time of growth of the destruction zone is approximately 40 μs, which is in good agreement with the time of existence of plasma formation at the surface of the target treated by laser plasma (~50 μs).*

**Keywords:** laser radiation, material destruction, crater, diagnostics.

### INTRODUCTION

Action of laser radiation on the surface of a solid is accompanied by various physical phenomena. One of them is acoustic emission of laser destruction zone of the material under the effect of elevated pressure in the vapor-plasma formation comprising evaporated material and hot air (laser flare). The surface of this zone starts to oscillate and radiates acoustic waves into the irradiated medium. Experiments and calculations demonstrated that the parameters of the emitted acoustic waves and the parameters of the destruction zone are unambiguously related [1]. Thus, the parameters of the destruction zone can be determined from the characteristics of acoustic emission, which can have obvious practical application.

In [1] the model of loaded zone radiating acoustic waves into an elastic medium was used to consider emission. However, time dependences and spectra of pressure pulses in the elastic wave calculated with the use of the given technique were in agreement with the available experimental data only starting from the second quarter of the period of pressure oscillations in the acoustic wave registered experimentally. The discrepancy can be due to generation of acoustic waves during growth of the forming inelastic deformation zone (rather than after completion of its formation).

The purpose of the present work is investigation of acoustic emission of the destruction zone directly during irradiation of the metal surface by laser pulses and study of the parameters characterizing time dependences of the pressure in the generated elastic wave and changes of sizes (in particular, depths) of irreversibly deformed zone on the surface of the irradiated sample.

---

[1]Yanka Kupala Grodno State University, Grodno, Byelorussia, e-mail: s.vasilijev@grsu.by; kakdelanik@mail.ru; ion_ne@mail.ru; nedolugov_vi@grsu.by; [2]Grodno State Medical University, Grodno, Byelorussia. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 9, pp. 134–139, September, 2016. Original article submitted October 9, 2015; revision submitted April 11, 2016.

 

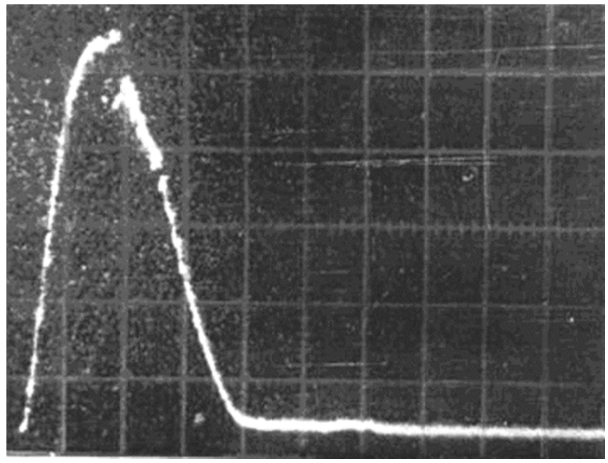

Fig. 1. Waveform of a laser pulse. Abscissa scale is 5 μs/div. The output pulse energy was 25 J.

**EXPERIMENTAL SETUP**

Radiation of a laser on ethanol solution of rhodamine 6G with a coaxial pumping lamp [2] after passage through a field stop and a focusing system was incident on a sample. The waveform of the laser pulse is shown in Fig. 1. One- and two-lens systems that allowed the image of the field stop to be obtained on the irradiated sample surface were used to focus laser radiation. The most uniform spot of focused radiation 3 mm in diameter with sharp edges was formed by the two-lens system with 12-fold image reduction and the field stop 40 mm in diameter. A portion of radiation of the rhodamine laser from the front face of the wedge was directed toward an IMO-2N energy meter whose input window was located in the rear focal plane of the lens. Radiation reflected from the rear face of the wedge was incident on a FÈK-14 coaxial photocell and was used to register the laser radiation waveform on an S8-13 storage oscilloscope.

To register acoustic waves formed under laser irradiation of the material, the pressure gauge located on the optical axis of the system was attached to the rear side of the irradiated sample. The signal from the pressure gauge was fed to the input of the S8-13 storage oscilloscope whose triggering was synchronized with the onset of the laser pulse using a GZI-6 generator of delayed pulses.

The gauge based on TsTS-19 piezoceramics equipped with a device for compensation of reflections [3–5] was used to register the acoustic wave pressure level. The choice of the gauge type was determined by a considerable (more than twofold) difference between piezomoduli $d_{31}$ and $d_{33}$ the consequence of which was predominant registration of the elastic pressure components normal to the working cut. The gauge bandwidth allowed signals with frequencies up to 1 MHz to be registered with high reliability. The time dependence of the pressure in the acoustic wave registered when the laser pulse with duration of 20 μs acted on a copper sample is shown in Fig. 2*a*.

The irradiated sample was inserted in one of the arms of the Mach–Zehnder holographic interferometer. The lengths of the interferometer arms were made equal within 1–2 mm. Radiation of the ruby laser operating in the free generation mode [6] with pulse duration of ~300 μs was used as probing one. Transverse modes of the ruby laser were selected by the field stop 2 mm in diameter placed in the resonator, and longitudinal modes were selected by the standard Fabry–Perot interferometer with a base of 25 mm used as an output mirror.

Probing radiation entered a collimator forming the parallel beam 40 mm in diameter that illuminated the interferometer. Such transverse sizes of the probing beam allowed us to investigate not only the laser erosive plasma flare (LEPF) with characteristic sizes of ~20 mm in the axial direction, but also the behavior of shock waves beyond the flare. The interferometer was connected to an SFR-1M camera working in the mode of time magnifier with a two-row

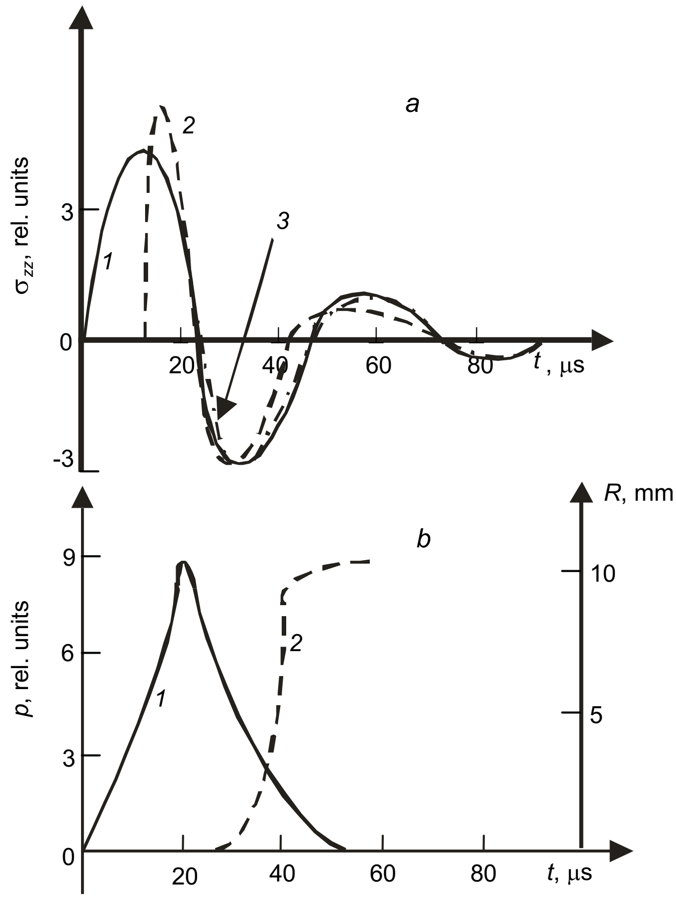


Fig. 2. Time dependences of the acoustic wave pressure level (*a*) under the action of the laser pulse with duration of 20 μs on the copper samples. Here curve *1* shows the experimental curve, curve *2* shows the result of calculation neglecting the crater growth during acoustic emission, and curve *3* shows the result of calculation taking into account the growth of the inelastic deformation zone according to the law $R(t) = R_{\max} \cdot \exp\left(\frac{t^2}{\tau_0^2}\right)$ for $t<0$ and $R(t) = R_{\max}$ for $t>0$; $\tau_0 = 40$ μs; (*b*) curves of the time dependences of the pressure level in the vapor-plasma cloud on the boundary of the irreversible deformation zone (curve *1*) and of the curvature radius of the inelastic deformation zone (curve *2*).

lens insert. This scheme allowed us to register time domain holograms of the focused LEPF image. Individual shots of holograms provided time resolution no worse than 0.8 μs (exposure time for a shot).

The spatial (in the radial direction) and temporal distributions of the refractive index in the LEPF were determined from the reconstructed interference patterns.

Since the contribution of a single electron to the refraction of plasma is 10 times greater than the contribution of a heavy particle [7], the refraction in plasma with average and high density is determined mainly by the electronic gas density. This allows one, using the technique described in [8], to calculate the spatial and temporal distributions of the electron density in the laser plasma.

At the initial moments of time (0–10 μs) corresponding to the leading front and the maximum of the pulse generated by the rhodamine laser, the electronic density was higher near the sample surface. Then (10–15 μs) the maximum of the electron concentration displaced from the irradiated surface. In later stages of the process, i.e., by the end of the acting pulse (15–20 μs), the electron density along the flare axis was leveled.

Pulsating inhomogeneities of the electron density that attenuated in the process of establishing quasi-stationary distribution of the density in the flare in late stages of its decay at $t > 40$ μs after the onset of laser irradiation of the metal sample were also detected.

## ACOUSTIC EMISSION OF THE LASER DESTRUCTION ZONE

To investigate acoustic emission, we take advantage of the model of loaded zone radiating acoustic waves into an elastic medium [1]. In the model we consider the destruction zone as a spherical segment of radius $R$, depth $d$, and diameter $2r_1$. The $z$ axis of the coordinate system is directed along the laser beam. It is essential that the geometrical sizes of the inelastic deformation zone change with time: $R = R(t)$, $d = d(t)$, and $r_1 = r_1(t)$, where $t$ is time.

In the elastic zone, the displacement vector of the acoustic wave can be expressed as a sum of the longitudinal and transverse components, each described by the corresponding wave equation. We seek a solution of these equations in the form of a sum of the volume and surface components due to the presence of the interface between the media directly in the zone of forming elastic oscillations. Taking into account the symmetry of the problem, the Fourier component of the displacement vector $\boldsymbol{A}$ assumes the form

$$\boldsymbol{A}(\omega) = A(\omega)\frac{\boldsymbol{r}}{r^3}(1 + ik_l r)\exp(-ik_l(r - R)) + B(\omega)(\boldsymbol{\rho}_0 k_R J_1(k_R\rho) + \boldsymbol{z}_0\chi_l J_0(k_R\rho))$$

$$\times\exp(-\chi_l(z - h)) + D(\omega)(\boldsymbol{\rho}_0\chi_t J_1(k_R\rho) + \boldsymbol{z}_0 k_R J_0(k_R\rho))\exp(-\chi_t(z - h)), \quad (1)$$

where ω is frequency, $A(\omega) = \tilde{A}(\omega)\exp(-ik_l R)$, $B(\omega) = \tilde{B}(\omega)\exp(-\chi_l h)$, $D(\omega) = \tilde{D}(\omega)\times\exp(-\chi_t h)$, $c_\ell$ and $c_t$ are longitudinal and transverse sound velocities, $k_R = \omega/c_R$, $c_R$ is the velocity of the Rayleigh elastic waves, $\chi_i = (k_R^2 - k_i^2)^{1/2}$, $\tilde{B}(\omega)$ and $\tilde{D}(\omega)$ are the oscillation amplitudes, and $J_i(x)$ are the Bessel functions.

Let us consider that the time dependence of the excess pressure exerted by the vapor-plasma formation on the surface of the spherical segment $r = R$ is known:

$$P\,|_{\,r=R} = p\,(t).$$

On the surface $z = h$ the excess (with respect to the pressure in the unperturbed medium) pressure in the plasma flare changes from $p(t)$ at $\rho = r_1$ to 0 at $\rho >> r_1$. Here ρ is the polar radius in the cylindrical system of coordinates, and the $z$ axis, as already indicated above, is directed along the laser beam. Since during experimental investigations the pressure gauge, as a rule, is placed on the axis of the process, of greatest interest is the time dependence of the pressure level in the fragment of the plane $\rho \sim r_1$. Therefore, we will consider that the time dependence of the pressure level is also close to $p(t)$ on the surface $z = h$.

As boundary conditions, we consider the conditions of equilibrium of the irreversible deformation zone boundary. In this case:

– $r = R$, $\sigma_{rr} = -r\,(t)$, and $\sigma_{r\theta} = \sigma_{r\varphi} = 0$ on the surface of the spherical segment;
– $z = h$, $\sigma_{zz} = \rho\,(t)$, $\sigma_{\rho z} = 0$, and $\sigma_{z\varphi} = 0$ on the boundary.

Here $\sigma_{ij}$ are the components of the pressure tensor; $r$, θ, and φ are the spherical coordinates (the origin of coordinates and the direction of the $z$ axis have already been specified; the angles φ in the spherical and previously assigned cylindrical systems of coordinates are set equal).

Since outside of the segment $R = R(t)$ the medium can be considered elastic, to establish a relationship between the pressure level and the deformation tensor components, we can take advantage of the Hook law [9] that in our case assumes the form

$$\left[\lambda\left(\frac{\partial A_r}{\partial r}+2\frac{A_r}{r}+\frac{1}{r}\frac{\partial A_\theta}{\partial \theta}+\frac{A_\theta}{r}\text{ctg}\,\theta\right)+2\mu\frac{\partial A_r}{\partial r}\right]_{r=R(t)}=-p(t)\,,$$

$$\left(\frac{\partial A_\rho}{\partial z}+\frac{\partial A_z}{\partial \rho}\right)_{z=h(t),\rho=\rho_1(t)}=0\,, \tag{2}$$

$$\left[\lambda\left(\frac{\partial A_\rho}{\partial \rho}+\frac{A_\rho}{\rho}+\frac{\partial A_z}{\partial z}\right)+2\mu\frac{\partial A_z}{\partial z}\right]_{z=h(t),\,\rho=\rho_1(t)}=-p(t)\,.$$

Here $A_i$ are the components of the displacement vector $\boldsymbol{A}$ in the spherical and cylindrical systems of coordinates and $\lambda$ and $\mu$ are the Lame coefficients. Substituting expressions for $A_i$ derived from Eq. (1) into system (2), we obtain for each moment of time $t$ a system of algebraic equations for $A(\omega,R,d,\rho_1)$, $B(\omega,R,d,\rho_1)$, and $D(\omega,R,d,\rho_1)$. Having determined these coefficients, we easily calculate the components of the elastic deformation vector (the displacement vector in the elastic wave) $\boldsymbol{A}(\omega,\boldsymbol{r})$ and the pressure (component of the elastic stress tensor) $\sigma_{zz}(\omega,R,d)$. To obtain the time dependence of the pressure in the elastic wave $\sigma_{zz}(t)$, we take the inverse Fourier transform of $\sigma_{zz}(\omega,R,d)$. In this case, it is necessary to consider that $R=R(t)$, $d=d(t)$, and $\rho_1=\rho_1(t)$, i.e.,

$$\sigma_{zz}(t)=\int_{-\infty}^{+\infty}\sigma_{zz}(\omega,R,d)\exp[i\omega t]d\omega=\int_{-\infty}^{+\infty}\sigma_{zz}(\omega,R(t),d(t))\exp[i\omega t]d\omega=\int_{-\infty}^{+\infty}\sigma_{zz}(\omega,t)\exp[i\omega t]d\omega\,.$$

Results of calculations of the first half-cycle of the dependence $\sigma_{zz}(t)$ for the indicated dependences $R=R(t)$ are shown in Figs. 3 and 4.

Calculations were performed for a copper sample with density in the elastic zone $\rho=8800$ kg/m$^3$ for velocities $c_t=2260$ m/s, $c_l=4700$ m/s, and $c_R=2113$ m/s at the maximal external pressure $p_{\max}=6\cdot10^5$ Pa and final parameters of the destruction zone $\rho_{1\max}=1.5\cdot10^{-3}$ m, $d_{\max}=0.1\cdot10^{-3}$ m, and $R_{\max}=11.25\cdot10^{-3}$ m. The best agreement with the experimental data was obtained for the time dependence of the crater curvature radius of the form $R(t)=R_{\min}\exp[kt^2]$. Figure 4 shows time dependences of the pressure in the elastic wave for the Gaussian law of growth of the crater curvature radius ($R(t)=R_{\max}\cdot\exp\left(\frac{t^2}{\tau_0^2}\right)$ for $t<0$ and $R(t)=R_{\max}$ for $t>0$) and the indicated times $\tau_0$ of growth of the inelastic deformation zone up to the maximal size $R_{\max}=11.25\cdot10^{-3}$ m. It can be seen that the best agreement is obtained for a crater growth time of 40 μs.

During calculations, different time dependences of the pressure on the boundary of the inelastic zone were considered. This allowed us to judge the behavior of the subsurface plasma. The best agreement with the experiment was obtained in the case when the plasma pressure exponentially increased to a maximum for 20 μs and then exponentially decreased to a minimum over the next 30 μs (Fig. 2*b*). Figure 2*b* shows the time dependence of the pressure in the vapor-plasma cloud on the boundary of the irreversible deformation zone and the time dependence of the curvature radius of the inelastic deformation zone.

As can be seen from Fig. 2*a*, consideration of the time dependence of the curvature radius allows results to be obtained that agree much better with the experiment data, including the first oscillation half-period, than pressure in an elastic wave. It is essential that the growth of the crater upon exposure of the copper sample to the laser flare lasts 40–50 μs, which is in good agreement with the time of existence of the plasma formation near the target (~50 μs). Thus, having registered the acoustic wave radiated upon exposure of a solid to pulsed laser radiation and using the method of mathematical modeling to achieve the best coincidence between the experimental data and the results of calculations for

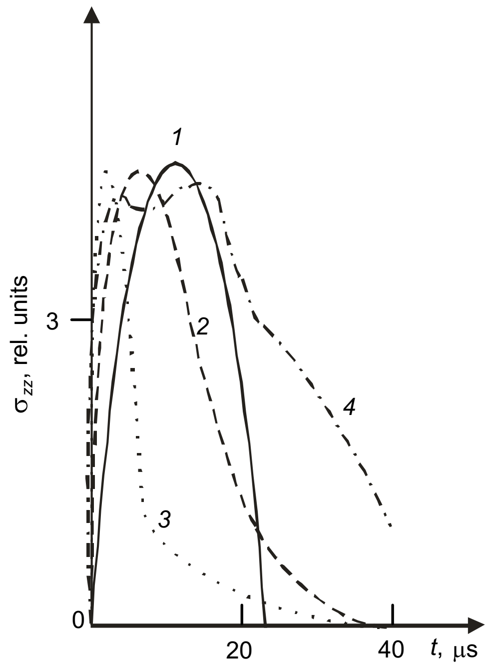


Fig. 3

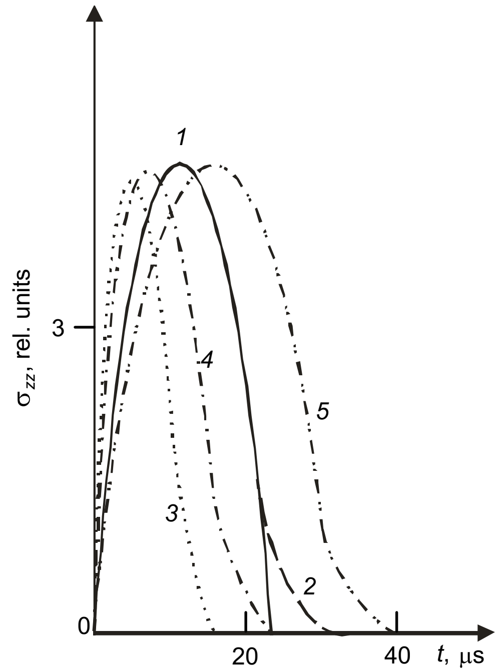


Fig. 4

Fig. 3. Dependences of the pressure in the elastic wave for different time dependences of the crater curvature radius growth. Here curve *1* shows experimental data (the first half-cycle), curve *2* is for an exponential dependence (time of crater growth was 50 μs), curve *3* is for a parabolic dependence (time of crater growth to its maximum size was 50 μs), and curve *4* is for a sinusoidal dependence (time of crater growth was 50 μs).

Fig. 4. Time dependences of the pressure in the elastic wave for the Gaussian law of the crater curvature radius growth $\left( R(t) = R_{\max} \exp\left(\frac{t^2}{\tau_0^2}\right),\ t<0,\ \text{and}\ R(t) = R_{\max}\ \text{for}\ t>0 \right)$ and different times of growth of the inelastic deformation zone. Here curve *1* shows experimental data (the first half-cycle), curve *2* is for $\tau_0$ = 40 μs, curve *3* is for $\tau_0$ = 20 μs, curve *4* is for $\tau_0$ = 30 μs, and curve *5* is for $\tau_0$ = 50 μs.

the model of loaded zone with moving boundaries radiating acoustic waves into the elastic medium, it is possible to determine the law of time growth of the irreversible deformation zone on the surface of the treated target.

## CONCLUSIONS

The application of the model of loaded zone with moving boundaries radiating acoustic waves into an elastic medium allows the law of time growth of the irreversible deformation zone on the sample surface subjected to pulsed laser-plasma treatment to be determined.

## REFERENCES


1. A. Yu. Ivanov, Acoustic Diagnostics of the Process of Laser Treatment of Materials [in Russian], Publishing House of Grodno State University, Grodno (2007).
2. A. A. Bakeev *et al*., Kvant. Elektron., **7**, No. 2, 349–354 (1980).
3. S. I. Pugachev, ed., Piezoceramic Transducers: A Handbook [in Russian], Sudostroenie, Leningrad (1984).
4. È. A. Simson and A. A. Taranukha, Akust. Zh., **39**, No. 5, 896–903 (1993).
5. E. S. Voronel' and L. P. Kiryushin, Izv. Sib. Otd. Ross. Akad. Nauk, Ser. Tekh. Nauk, No. 2, 75–79 (1991).
6. V. I. Nedolugov, in: Physical Methods of Research of Transparent Inhomogeneities [in Russian], F. E. Dzerzhinsky House of Scientific and Technical Propaganda, Moscow (1990), pp. 31–32.
7. C. West, Holographic Interferometry [Russian translation], Mir, Moscow (1982).
8. Yu. I. Ostrovskii, M. M. Butusov, and G. V. Ostrovskaya, Holographic Interferometry [in Russian], Nauka, Moscow (1977).
9. L. D. Landau and E. M. Lifshits, Elasticity Theory [in Russian], Nauka, Moscow (1987).