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Investigation of crater form and dimensions evolution during laser treating of materials

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Abstract. Acoustic emission of a zone of the destruction formed during influence of pulse laser radiation on a surface of metal is considered. Dependence of the time form of acoustic fluctuations on parameters of an irradiated material and the law of increase in depth of a crater was estimated. It is revealed, that at action on a surface of the copper sample of a laser impulse duration ~ 20 μs time of growth of a zone of destruction makes approximately 40 μs. It is shown also that having detected a diffraction picture appearing on incidence of SHF-radiation on the surface of solid and having achieved during the experiment the best coincidence of the experimental and calculated using the computer model data one can define the character of the zone of destruction on the surface of structure being under treatment relief.

1. Introduction

Laser treating of solids is accompanied by several phenomena. One of these phenomena is an acoustic emission of irradiated matter destructed zone. The experiments and theoretical investigations show the existence of simple connection between the parameters of emitted acoustic waves and the characteristics of destructed zone [1]. Thus estimating the properties of the acoustic wave one can estimate the parameters of destructed zone [2]. The authors of mentioned works have obtained their results using the model of a loaded zone radiating waves into elastic medium. Calculated with the help of this model temporal dependences of pressure of an elastic wave correspond satisfactory to the experimental data only beginning from the second quarter of the pressure of elastic wave oscillations because of the acoustic wave generation during the growth of the zone of non-elastic deformation.

Our aim was to investigate emission of the acoustic waves generated on the laser treating of solids during the laser radiation action on the metal surface and estimation of the dependence of temporal parameters of the pressure of generated elastic wave and the temporal dependences of the geometrical properties of irreversibly deformed zone on the surface of the irradiated sample. The second purpose of research was to develop the new method of determination of geometrical parameters of destructed zone in real time scale, based on the features of SHF-radiation diffraction on the different objects with complicated form are perspective.

2. Acoustic emission of laser destruction zone

Investigating the acoustic emission let us use the model of a loaded zone radiating waves into elastic medium. Corresponding to this model let us consider the destructed zone as a spherical segment with the curvature radius R, depth d and diameter $2r_1$. z-ax of the coordinate system is directed along the laser beam. It is important that the parameters of the irreversibly deformed zone are changing on the time: $R = R(t)$, $d = d(t)$, $r_1 = r_1(t)$; here t is the time.

The displacement vector in an elastic zone consists of a longitudinal and a transversal components, $\vec{A} = \vec{A}_l + \vec{A}_t$, and each of them can be described by corresponding wave equation. Because of the presence of the media board direct in the elastic wave generating zone the solution of the wave equations system we shall search as a sum of the volume and the surface components

$$\vec{A}_l = \vec{A}_{lO} + \vec{A}_{l\Pi} = \nabla\psi_O + \nabla\psi_\Pi \quad ,$$
$$\vec{A}_t = \vec{A}_{tO} + A_{t\Pi} = \vec{A}_{t0} + rot(\vec{B}) \quad .$$

With regard to the symmetry of our problem, $\vec{A}_{t0} = 0$, scalar potential $\psi_0(\omega) = -\tilde{A}(\omega)\cdot\dfrac{\exp(-ik_l r)}{r}$, $\psi_\Pi(\omega) = -Z_0(k_R\rho)\cdot(\tilde{B}(\omega)\cdot\exp(-\chi_l z) + \tilde{Q}(\omega)\cdot\exp(\chi_l z))$, $B_\varphi(\omega) = Z_1(k_R\rho)\cdot(\tilde{D}(\omega)\cdot\exp(-\chi_t z) + \tilde{S}(\omega)\cdot\exp(\chi_t z))$, $B_\rho = B_z = 0$.

Here ω is a frequency, $k_\ell = \omega/c_\ell$, c_ℓ and c_t – longitudinal and transversal sound velocities,

$\tilde{A}(\omega)$ – wave amplitude, $k_R = \omega / c_R$, c_R – surface wave velocity, $\chi_i = (k_R^2 - k_i^2)^{1/2}$, $\tilde{B}(\omega)$, $\tilde{D}(\omega)$, $\tilde{Q}(\omega)$, $\tilde{S}(\omega)$, – oscillation amplitudes, $Z_i(x)$ – spherical function. When $\rho \to 0$ and

$z \to \infty$ the result must remain finite, therefore $Z_i(x) = J_i(x)$ (Bessel function), $\tilde{Q}(\omega) = \tilde{S}(\omega) = 0$, and

$$\vec{A}(\omega) = A(\omega)\frac{\vec{r}}{r^3}(1 + ik_l r)\exp(-ik_l(r-R)) + B(\omega)(\vec{\rho}_0 k_R J_1(k_R\rho) + \vec{z}_0\chi_l J_0(k_R\rho))\times$$
$$\times\exp(-\chi_l(z-h)) + D(\omega)(\vec{\rho}_0\chi_t J_1(k_R\rho) + \vec{z}_0 k_R J_0(k_R\rho))\exp(-\chi_t(z-h)) \qquad (1),$$

where $A(\omega) = \tilde{A}(\omega)\cdot\exp(-ik_l R)$, $B(\omega) = \tilde{B}(\omega)\cdot\exp(-\chi_l h)$, $D(\omega) = \tilde{D}(\omega)\cdot\exp(-\chi_t h)$.

Let us consider that on the surfaces $r = R$ and $z = h$ temporal dependence of pressure in the plasma cloud is

$$P/_{r=R} = p(t) .$$

On the surface of spherical segment $R = R(t)$ $\sigma_{rr} = -p(t)$, $\sigma_{r\theta} = \sigma_{r\varphi} = 0$; on the surface $z = h$ $\sigma_{zz} = \rho(t)$, $\sigma_{\rho z} = 0$, $\sigma_{z\varphi} = 0$. Here σ_{ij} are the components of the stress tensor, r, θ, φ are the coordinates of spherical system.

Out of the spherical segment $R = R(t)$ medium is elastic, and so [3]

$$\left[\lambda\left(\frac{\partial A_r}{\partial r} + 2\frac{A_r}{r} + \frac{1}{r}\frac{\partial A_\theta}{\partial\theta} + \frac{A_\theta}{r}ctg\,\theta\right) + 2\mu\frac{\partial A_r}{\partial r}\right]_{r=R(t)} = -p(t),$$
$$\left(\frac{\partial A_\rho}{\partial z} + \frac{\partial A_z}{\partial\rho}\right)_{z=h(t),\rho=\rho_1(t)} = 0, \qquad (2)$$

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

Here A_i are the components of the displacement vector $\vec{A}$, λ, μ are the Lame coefficients.

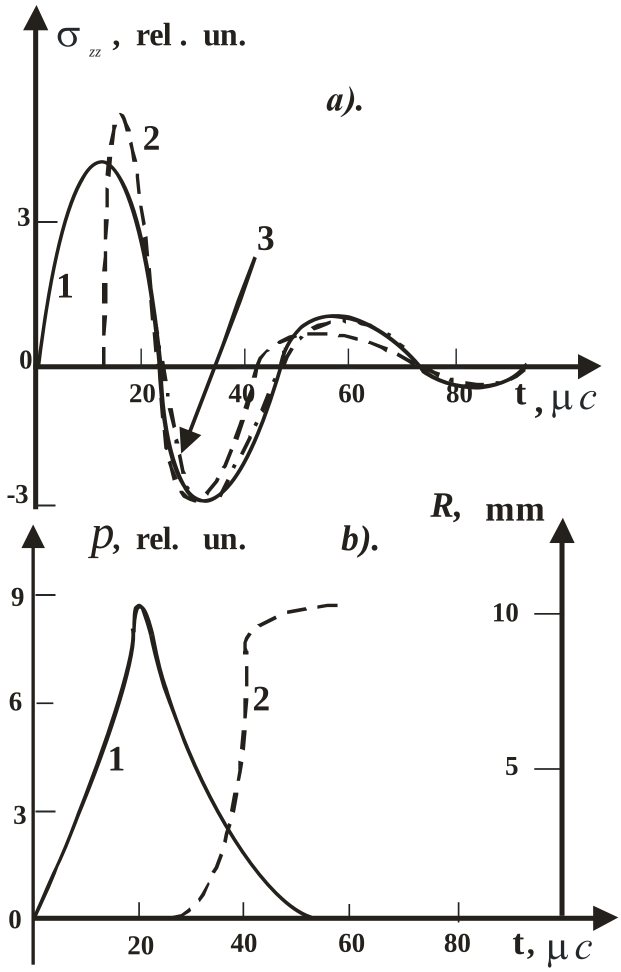

Figure 1. *a).* Temporal dependences of pressure of acoustic wave on the action of laser pulse with duration of 20 μs on cupper sample: 1 – experimental dependence [2]; 2 – dependence calculated without account of crater growth [4]; 3 – dependence calculated with account of crater growth. *b).* 1 – temporal dependences of pressure of plasma cloud on the border of irreversibly deformed zone; 2 – temporal dependences of curvature radius.

Substituting A_i from the equation (1) to the system (2) we can calculate for each temporal moment $A(\omega,R,d,\rho_1)$, $B(\omega,R,d,\rho_1)$, $C(\omega,R,d,\rho_1)$, $\sigma_{zz}(\omega,R,d)$ and

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

The results of the calculations with $R(t) = R_{\max} \cdot \exp\left(\frac{t^2}{\tau_0^2}\right)$ for $t < 0$ and $R(t) = R_{\max}$ for $t > 0$ are presented on the figure 1; τ_0 = 40 μs .

Evidently that at action on a surface of the copper sample of a laser pulse duration ~ 20 μs time of growth of a zone of destruction makes approximately 40 μs , that will well be coordinated with time of existence of plasma formation at a surface of the target exposed to laser-plasma processing (~ 50 μs). Use of model of the loaded area with the moving borders radiating acoustic waves in the elastic medium allows to solve the important practical problem – the definition of a law of time growth of a zone of irreversible deformations on a surface of the sample exposed to pulse laser-plasma processing.

3. Use of SHF-diapason electromagnetic waves diffraction for the crater evolution diagnostics

The second purpose of research was to develop the new method of determination of geometrical parameters of destructed zone in real time scale. In this research the modeling and calculations were realized with the help of the program set CST Microwave Studio – a system of SHF-devices modeling based on the method of approximation and the method of definite integrals in temporal area [5].

The pictures of diffraction of SHF-radiation on the models of the structures with different dielectric penetrability periodicity including periodical structures (figure 2). Parameters of structure represented at fig. 2, are following. 9x9 right-angled insulators with dimensions 1x1x9 мм; dielectric penetrabilities ε_1=100, ε_2=200, ε_3=300. The diffracted radiation direction diagrams (figure 3) was obtained in SHF-diapason on the frequency f = 10.0*10^9 s^{-1}.

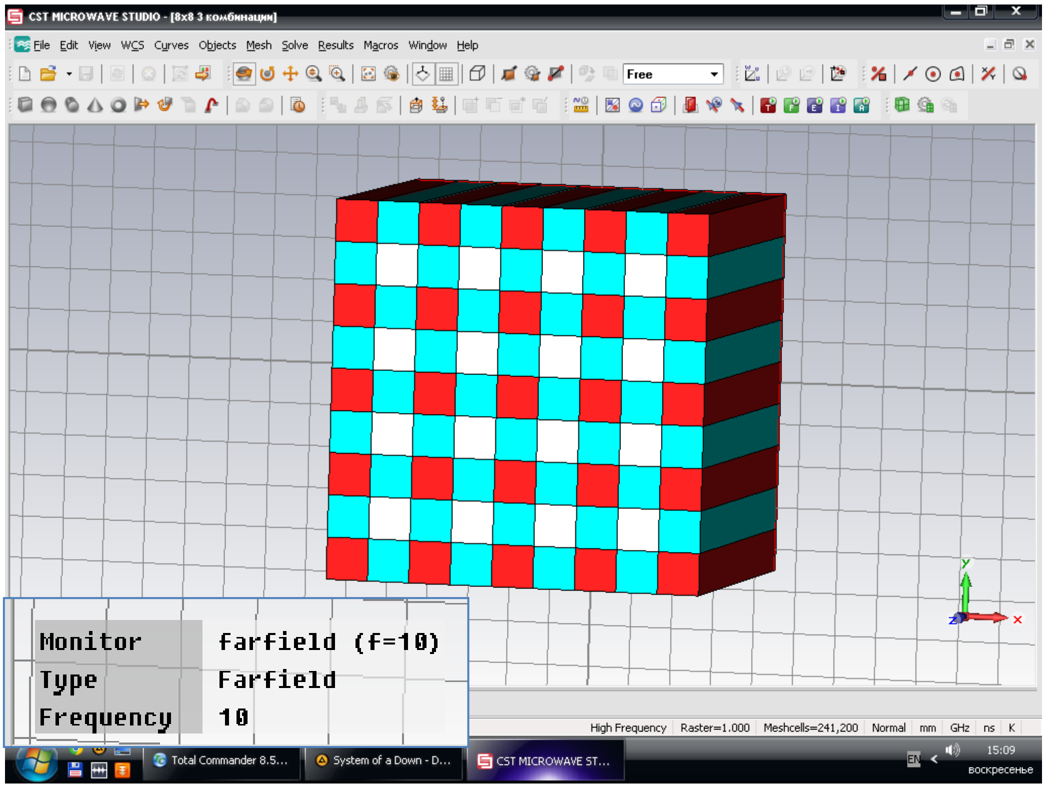

Figure 2. Computer model of periodical structure in CST Microwave Studio product.

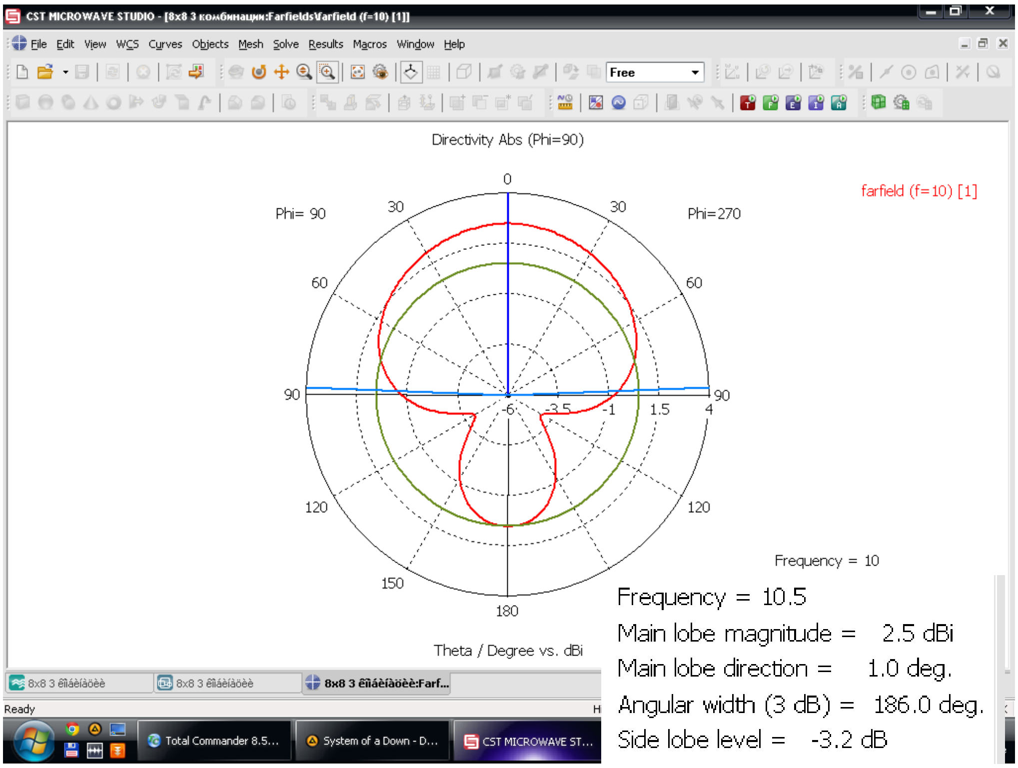

Figure 3. Direction diagram of described structure obtained on the frequency f = $10.5*10^9$ s^{-1}.

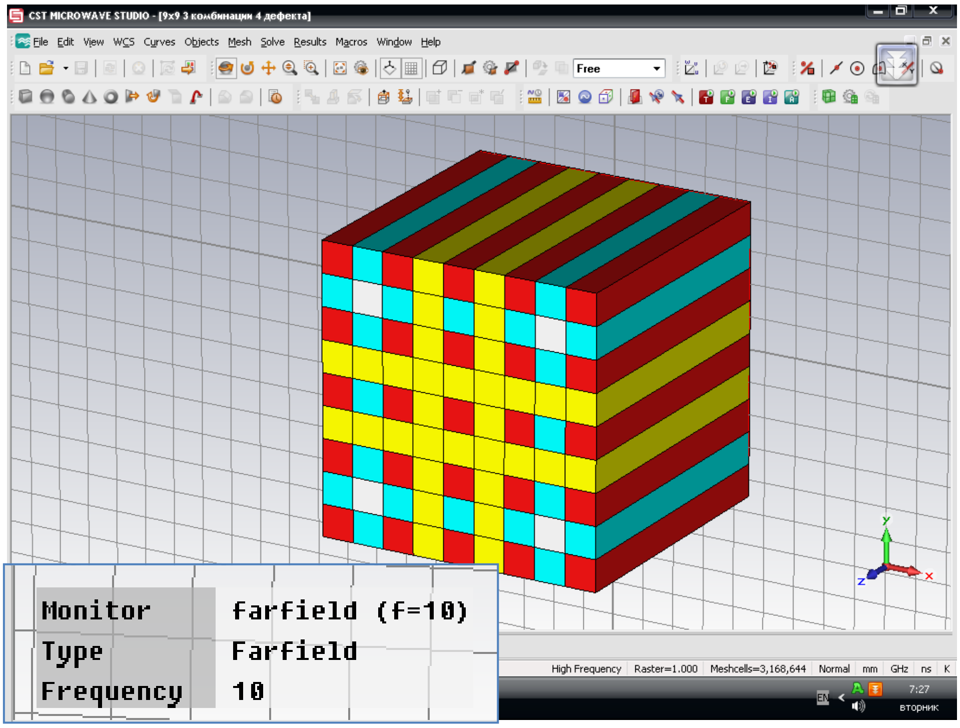

Figure 4. Computer model of periodical structure with some types of unperiodicity and defects in CST Microwave Studio product.

Figure 4 represents a of periodical structure with some types of unperiodicity and defects.

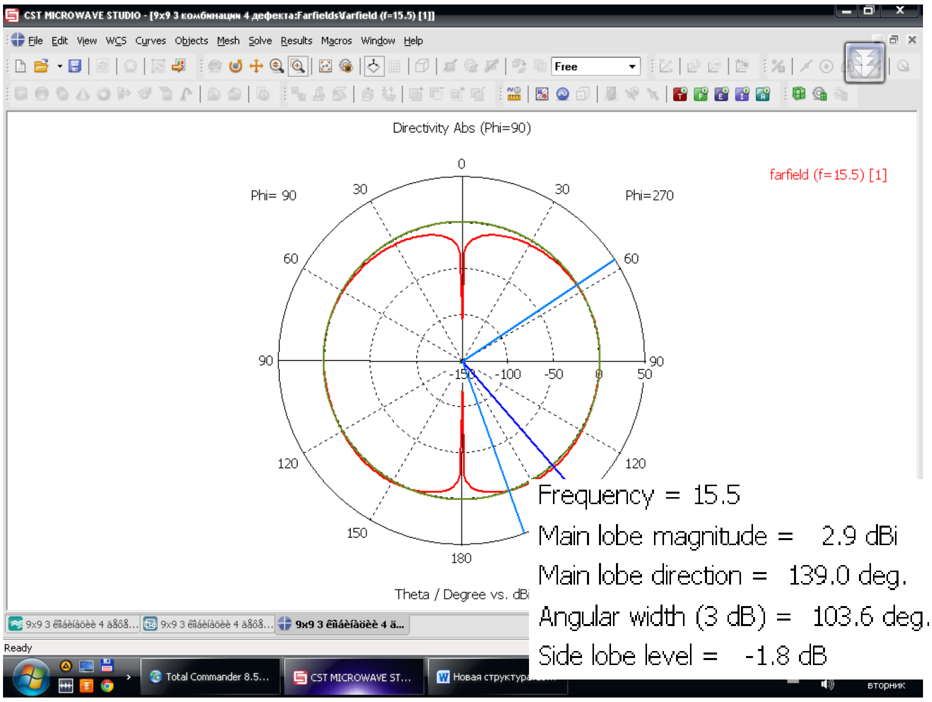

Figure 5. Direction diagram of described periodical structure with some types of unperiodicity and defects obtained on the frequency f = 15.5*10^9 s^{-1}.

Figure 5 represents the diffracted radiation direction diagram of periodical structure with some types of unperiodicity and defects obtained in SHF-diapason on the frequency f = 10.0*10^9 s^{-1}.

The results of modeling showed a considerable difference of the diffracted radiation direction diagrams obtained using some different objects. Using the distinctive parameters of diffractive reflection curve one can solve with the definite precision the reverse problem of character of defects of the surface of structure being under treating determination. The SHF-radiation admission spectrums for the described structures are also obtained. They are also different.

4. Conclusion

So having detected a diffraction picture appearing on incidence of SHF-radiation on the surface of solid and having achieved during the experiment the best coincidence of the experimental and calculated using the computer model data one can define the character of the zone of destruction on the surface of structure being under treatment relief.

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