A mathematical modeling of surface periodic relief after nanosecond laser processing

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Abstract

The paper proposes a mathematical model of the material surface periodic relief formation after nanosecond laser processing. The effect of a transparent condensed medium on the periodic structures formation on the material surface is shown. Mathematical modeling of temperature fields in the material during laser processing was carried out. It is shown that the surface layers undergo rapid melting, evaporation and transition into a plasma state. Modeling of plasma pressure showed that large pressure values occur on the material surface during irradiation, which are much higher during processing in a transparent condensed medium than in air. The correlation between the conducted modeling and the conducted experiments (determination of the recoil impulse of the ablation products and SEM images of the steel surface) is shown. The main parameters on which the wavelength of the solidifying material depends are determined.

Keywords

Nanosecond laser, mathematical modeling, periodic relief

1. Introduction

There are many different ways to modify the surface of materials. One of the most modern, technological and precise is laser processing [1-4]. This technology makes possible to obtain a structure and properties in the near-surface layers of the material that are radically different from the structure and properties of the base material [5-8]. As a result, the product after laser processing can have much better characteristics, which increases its reliability, service life, etc.

It should be noted that in order to increase the processing depth, as well as to obtain various structures on the surface of materials, in addition to the technological parameters of the laser installation itself (laser pulse energy, pulse duration, wavelength, etc.) [9-11], the transparent condensed medium (water, epoxy resin, etc.) in which processing is carried out also affects [12]. It allows to redistribute the energy that reaches the surface of the processed material, increase the plasma pressure and, as a result, the action of shock waves in the depth of the material, in addition, some elements of the transparent condensed medium can penetrate into the near-surface layers of the processed material.

Therefore, modeling the processes during laser treatment is very important in order to optimally choose laser irradiation regimes, which is useful for obtaining a predetermined

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periodic relief of various materials, because field studies are usually much more expensive than mathematical modeling.

2. Modeling of the temperature field during laser processing of materials

To modeling the temperature fields in the material, it is necessary to solve the thermal conductivity equation and one of the solutions is the next equation:

$$T(z,t) = \frac{2q\sqrt{at}}{\lambda} ierfc(\frac{z}{2\sqrt{at}}), \tag{1}$$

where
q – energy flux density;
t – laser pulse duration;
a – coefficient of thermal conductivity of the material;
λ – thermal conductivity;
z – depth of the heated layer;
ierfc (u) – probability integral function.

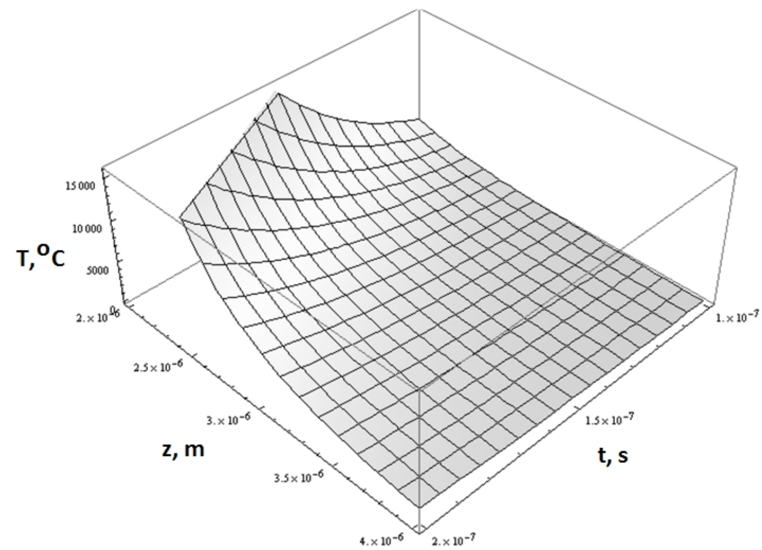


Figure 1: Temperature distribution in steel during irradiation in a transparent condensed medium.

Figure 1 shows the modeled distribution of the temperature field along the depth of the irradiated material. We can see that the temperature in the thin near-surface layer is several times higher than the melting temperature during processing. As a result, the material intensively melts, evaporates and turns into plasma.

These data are confirmed by scanning electron microscopy images of steel surfaces after nanosecond laser treatment in water (Figure 2). It can be seen that the surface underwent melting, intense boiling, which is evident from the number of pores. The periodic waves is clearly directed from the center of irradiation to the edges of the laser spot, which also indicates the plasma pressure and the recoil impulse of the ablation products.

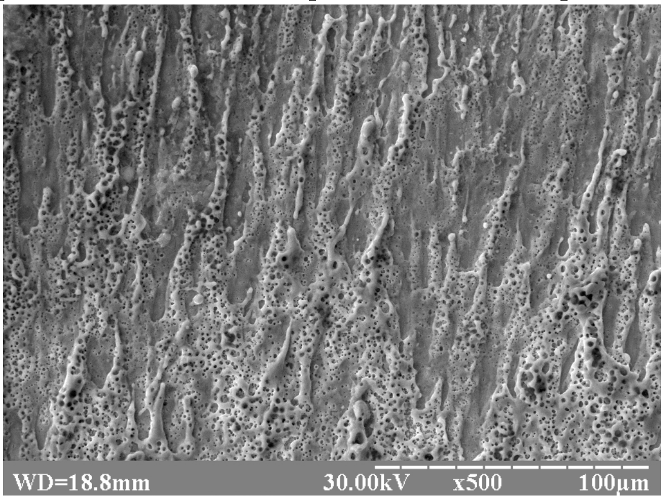


Figure 2: SEM image of steel surface after nanosecond laser processing

3. Modeling of the plasma pressure during laser processing of materials

The pressure during irradiation of materials in air can be determined by the formula:

$$P_{pl} = (a_{pl}t)^{-1/3} I^{3/4}, \quad (2)$$

where

I – intensity of laser radiation;

t – laser pulse duration;

α_{pl} - coefficient characterizing plasma properties.

To modeling the plasma pressure during laser processing in a transparent condensed medium, it is convenient to use the formula:

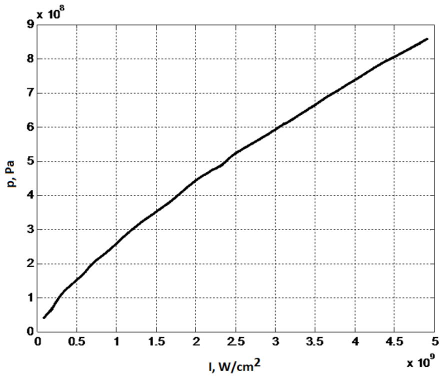
$$p = \sqrt{q\,\frac{\gamma-1}{\gamma}\cdot\frac{\rho_1 D_1\cdot\rho_2 D_2}{\rho_1 D_1+\rho_2 D_2}} \quad (3)$$

where

γ – adiabatic index,

D_1, D_2 – propagation speeds of the compression wave front;

ρ_1, ρ_2 – densities of unexcited mediums 1 and 2.



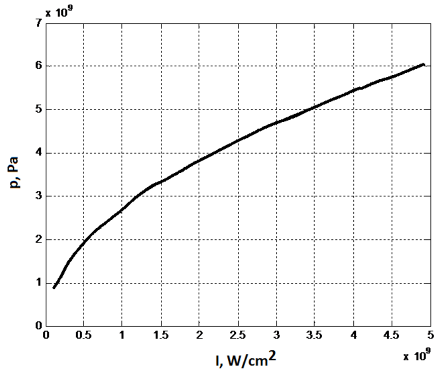


Figure 3: Dependence of plasma pressure on the intensity of laser radiation during processing in air

Figure 4: Dependence of plasma pressure on the intensity of laser radiation during processing in transparent condensed medium

Figures 3 and 4 show that high pressures occur on the surface of materials during nanosecond laser irradiation. Moreover, the plasma pressure during irradiation in a transparent condensed medium differs from the pressure during irradiation in air by almost 10 times at the same laser pulse intensities.

Conducted experiments to determine the recoil impulse using the pendulum method of ablation products during irradiation (Figure 5), showed that when irradiated in a transparent condensed medium the recoil impulse is an order of magnitude higher than the recoil impulse when processed in air. These data correlate with the calculations that were made above. It is shown that a transparent condensed medium can change the form and structure of the obtained periodic relief on the surface of materials after irradiation.

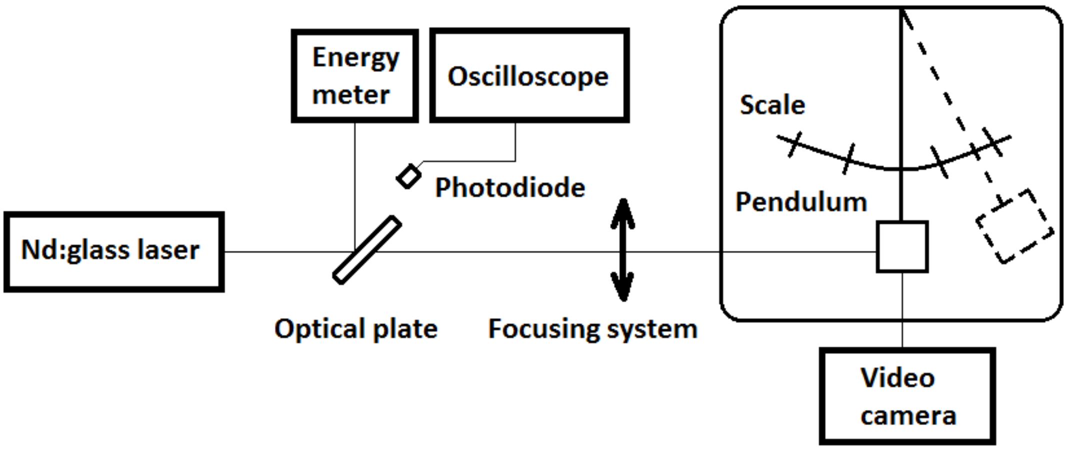


Figure 5: Recoil impulse pendulum method investigation scheme.

4. Some features of the periodic relief formation on the material surface after laser processing

One of the possible reasons for the appearance of periodic relief on the surface of the material after laser treatment is the formation of instabilities due to the occurrence of thermocapillary processes, which are associated with the dependence of the surface tension index of the heated material on temperature and the subsequent inhomogeneous melting. This process is also influenced by the plasma pressure and recoil impulse.

The pressure pulse causes a harmonic wave on the molten surface and a periodic relief is formed in the horizontal direction, and the oscillations decay exponentially in depth. Then we can obtain the dispersion equation, where the angular frequency ω is related to the wave vector κ:

$$\omega = \sqrt{\frac{\sigma}{\rho}\kappa^3} \qquad (4)$$

where

ρ – melt density,

σ – is the surface tension coefficient of the liquid metal layer melted by a laser pulse.

From this formula, the group velocity is determined as the derivative of the angular frequency along the wave vector:

$$\vartheta = \left(\frac{\sigma}{\rho}\right)^{1/2} \frac{9}{4} \kappa^{1/2} = \left(\frac{\sigma}{\rho}\right)^{1/2} \frac{9}{4} \left(\frac{2\pi}{\lambda}\right)^{1/2} \qquad (5)$$

And now is possible to find the wavelength of the solidifying material:

$$\lambda = \frac{2\pi}{\vartheta^2}\frac{\sigma}{\rho} \qquad (6)$$

The wavelength of the periodic relief varies depending on the material, its density, the value of the surface tension coefficient of the melt, the speed of sound in it, laser flux density and the conditions of irradiation. These data are confirmed by SEM images of steel surfaces after irradiation in a transparent condensed medium. (Figure 2).

5. Conclusions

The work carried out mathematical modeling of the main factors that affect the formed periodic relief on the surface of materials after nanosecond laser processing: temperature fields in the material, plasma pressure and the recoil impulse of the ablation products, and also showed the influence of thermophysical properties and the surface tension coefficient on the final wave length of frozen periodic relief. Modeling was implemented in the MATLAB system using physics and mathematical methods. Also, the modeling results were compared with real experiments and SEM images.

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