MODELING OF STRUCTURE OF DEPOSIT FORMED BY LASER-INDUCED DEPOSITION OF METALS FROM GAS PHASE

A.V. Nedolya, E.Yu. Mazyar, and I.N. Titov

Department of Applied Physics, Zaporizhzhya National University, 66, Zhykovsky str., 69600, Zaporozhzhya, Ukraine
(Received 5 June 2007)

The mathematical model that describes adequate the laser-induced process of metal deposition from gas phase on dielectric substrate is suggested. In the result of calculation, the temperature field distribution in deposited materials and deposit profiles for different process stages are obtained. The material deposition rate in the moment of deposited particle contacting with free surface is calculated. The explanation of mechanism of formation of irregular form deposits at the initial stage of deposition is proposed.

Introduction

Many problems on investigation of laser-induced deposition of materials are connected with stability of deposition process. The essence of the problem is appearing of different instabilities at some radiation parameters (power, beam radius) that lead to rod-like form depositions with very irregular geometry of surface [1-5].

The aim of the work is numerical investigation of temperature field in deposited materials and law of evolution of deposit form under continuous laser beam.

1. Statement of the problem and mathematical model

We consider that laser radiation with Gauss special distribution of intensity on beam cross-section is normal to dielectric substrate surface. The distribution of temperature in deposited materials at each moment of time is described by stationary equation of heat conductivity

$$\frac{1}{\mathrm{r}}\frac{\partial}{\partial \mathrm{r}}\left[k(T)\frac{\partial T}{\partial \mathrm{r}}\right]+\frac{\partial}{\partial z}\left[k(T)\frac{\partial T}{\partial z}\right]=0\,, \quad (1)$$

where k is the heat conductivity coefficient of the material. The $\partial T/\partial t$ component in heat conductivity equation in laser-induced tasks can be neglected, as the typical radius of beam r_0 and deposit is on order of 10 μm, thickness of the deposit layer h is 10÷100 μm, deposition time is $\tau_d \sim 10$ s. It means that characteristic heat conductivity time is $\tau_T \sim r_0^2/a \sim h^2/a << \tau_d$ (a is the temperature conductivity coefficient) and that characteristic process times are sufficient for the stationary temperature distribution $T(r, z)$ to reach the steady state.

It is necessary to add the boundary condition to heat conductivity equation (1)

$$T\Big|_{z,r=\infty}=T_n\equiv 300K,\; -k\left.\frac{\partial T}{\partial n}\right|_s = \mathrm{I_n} - \mathrm{I_T}, \quad (2)$$

where $\mathrm{I_n}$ is the normal to surface component of laser radiation intensity. We think that z-axes and $\vec{n}$ normal line are directed from the material.

The temperature loss intensity will be considered as constitute magnitude

$$\mathrm{I_T} = \mathrm{I_0}. \quad (3)$$

As one can see from works [2, 6, 7], owing to the fact that the reaction rate is not large, we can neglect the diffusion limitation influence on deposition process dynamics. It means that the deposition rate W is described by the following law

$$W = k_0 \exp\left\{-\frac{T_a}{T}\right\} = \frac{d\Delta}{dt}, \tag{4}$$

where Δ is the deposit thickness change, T_a is the activation temperature. It is necessary to note that the change occurs on normal direction to the material surface.

The formulated mathematical model describes the laser-induced material deposition from liquid-molecular gas compounds; for example, it may be WCl_6, WF_6, SiH_4. In this case the characteristic activation temperatures are $T_a \approx 3 \cdot 10^2$ K and the liquid phase does not appear.

2. Results of numerical modeling

For the purpose to analyze the deposition process of metallic particles on dielectric substrate in conditions of continuous stationary laser radiation, the numerical integration of (1)-(4) was performed (at the following parameter values: T_0=300 K, I_0=10^7 W/m^2, T_a=10^4 K, R=10 µm, H= 100 µm; for the gas temperature conductivity coefficient the linear dependence versus temperature is considered $K_g=K_{gn}T/T_0$, where K_{gn}=$3 \cdot 10^2$ W/mK).

The results of numerical integration have shown (Figs. 1 and 2) that maximum temperature is achieved in the deposited rod points that are at a distance of r=7 µm from the main rod (in dependence on z). The distance is about ¾ of deposit radius. It means that at the initial stage the saddle-shaped surface structure is formed due to non-uniform distribution of power density on laser beam radius, and radial heat escape dominating due to size effect influence (when the deposit radius is much larger than its thickness R>>H). Here temperature decreases monotonically at small r (near the rod axes) and on the lateral surface of the deposit, this coincides with experimental results of works [1, 8] and explains the heat escape to gas phase.

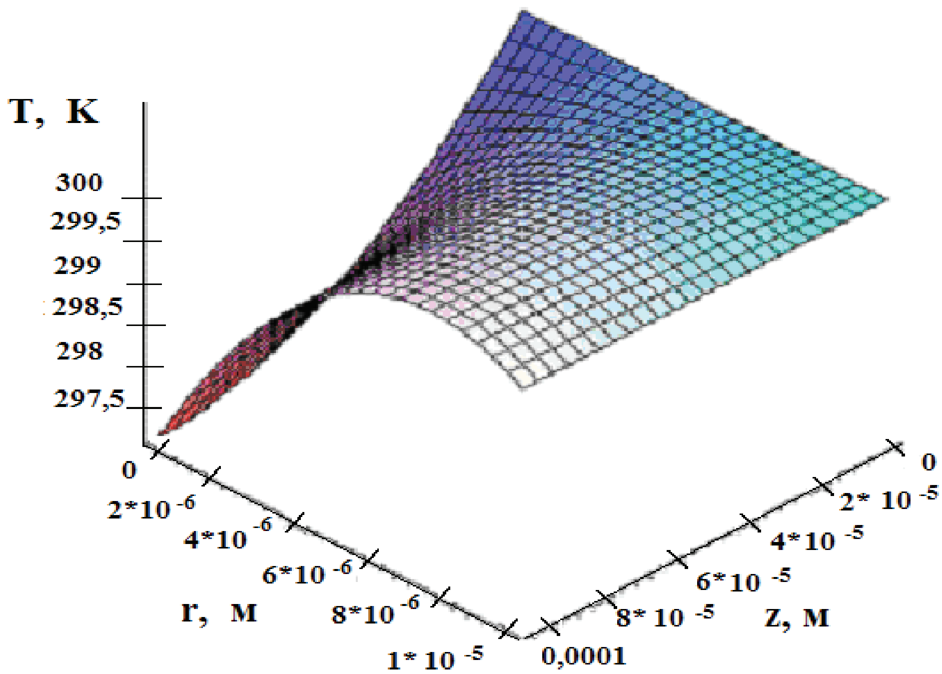

Figure 1. Temperature distribution in the deposited material.

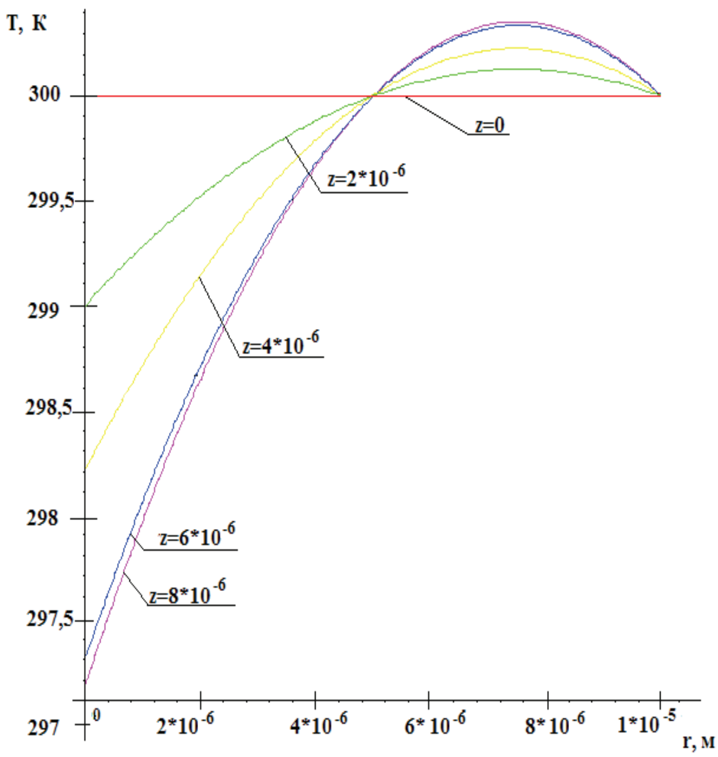

Figure 2. Distribution of *T(r)* for various *z*.

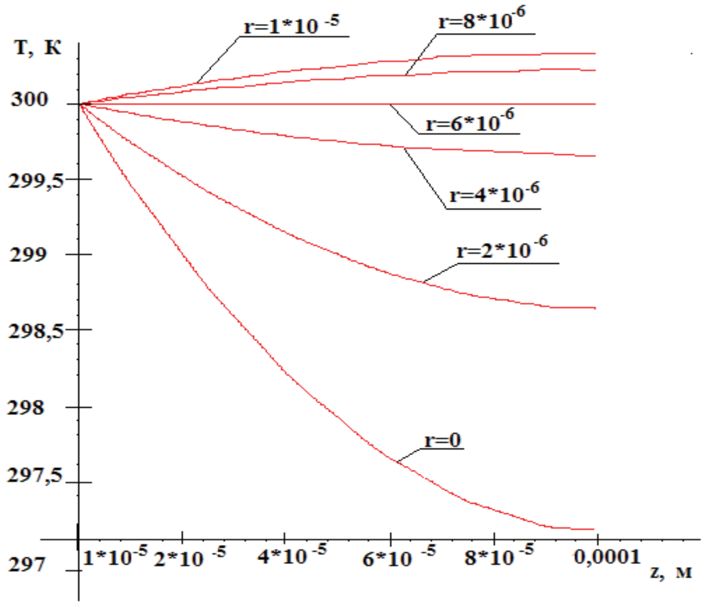

Figure 3. Distribution of *T(z)* for various *r*.

Analysis of the temperature distribution by deposit thickness *T(z)* (Fig. 3) has shown that at $r>6$ μm the temperature increases along the rod height, and at $r<6$ μm the temperature decreases. The following growth of the deposit thickness levels gradually the size effect, and we can observe stabilization of the temperature distribution (Fig. 3). This, in its turn, gradually leads to smoothing of external surface form and cylindrical rod formation.

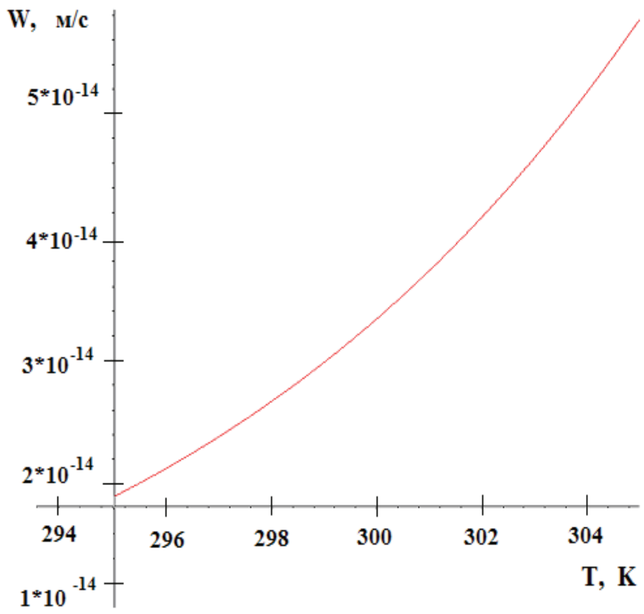

Figure 4. Temperature dependence of the deposition rate *W*.

The calculation of deposition rate temperature dependence *W(T)* (Fig. 4) in the moment of time t_0 (when the deposit only reaches the surface) has shown the deposition rate increase with temperature; e.g., as the temperature in the laser beam center is larger than in the border (due to Gauss distribution of intensity) the deposition rate is large there. So, in condition where the size effect is leveled, the effect of this process increases that leads finally to surface smoothing.

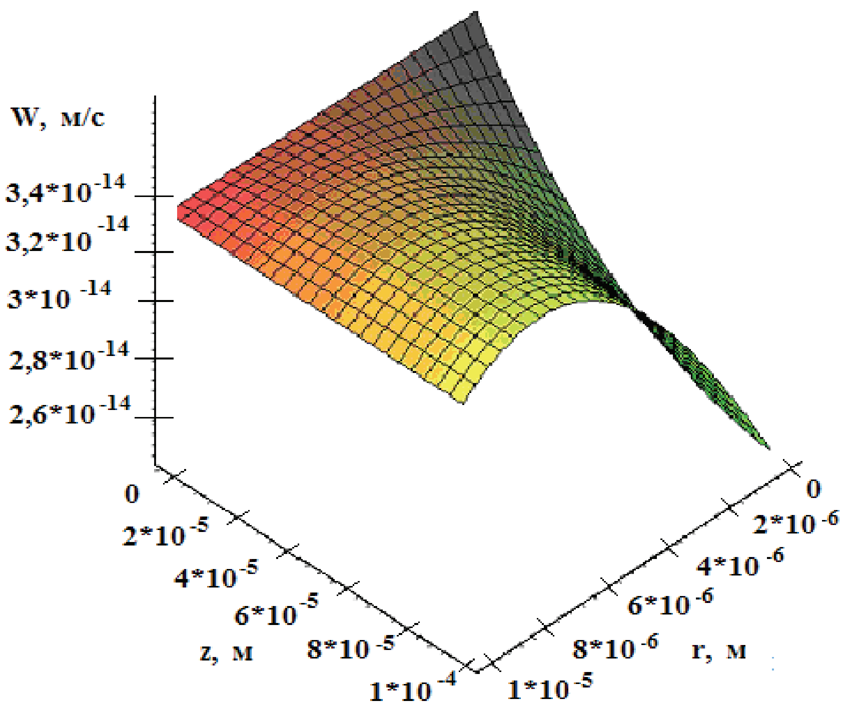

Figure 5. Distribution of the deposition rate *W(r, z)*.

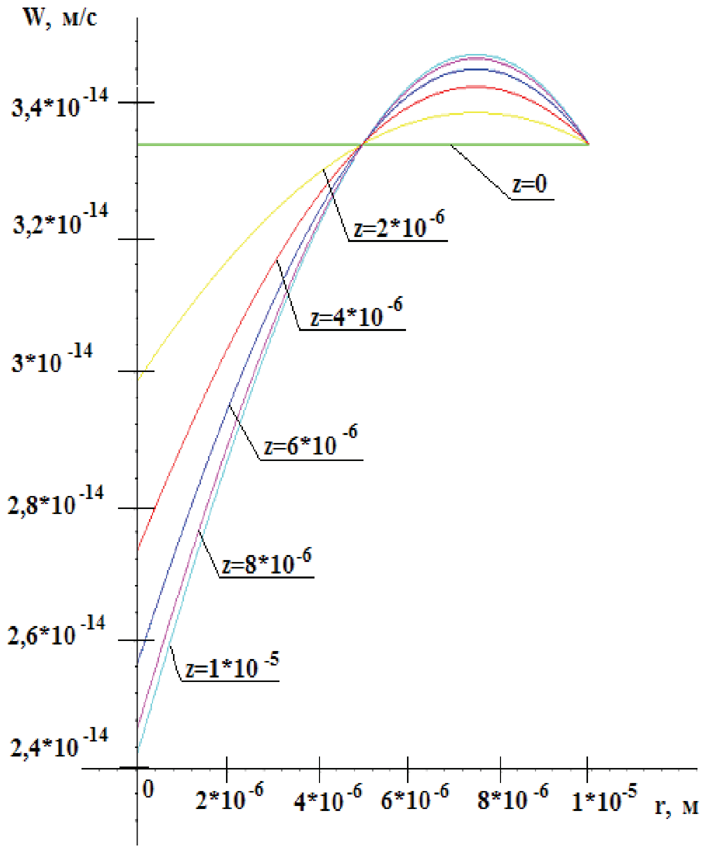

Figure 6. Distribution of the deposition rate *W(r)* at various *z*.

If the temperature distribution is known the material deposition rate *W(r,z)* can be calculated (Fig. 5). One can see that the deposition rate is maximum at a distance r=7÷8 μm from the rod axes, this coincides with temperature distribution analyses and the deposition rate distribution *W(r)* at various *z* (Fig. 6).

Since deposition rates on the deposit surface are various and proportional to the deposit thickness

$$W \sim \Delta \tag{5}$$

the surface form of the deposited material will be irregular, especially at the first stage of precipitation.

Conclusions

Thus, the laser-induced model of deposition subjected to constant intensity of heat losses is proposed. The model is described by the metal deposition from low-molecular gas compounds on dielectric substrate.

It is adjusted that deposition character with appearing non-trivial rod-like structure of the deposit may be stipulated both by instability of the deposition process itself and by combination of geometrical factors with features of heat interchange with gas atmosphere, e.g., size effect influence and its leveling with time.

The model allows determination of the deposit size parameters at which the uniform external surface of the deposit is formed, allowing evaluation of the minimum size of objects that can be formed by laser-induced deposition.

References

[1] N.V. Karlov, N.A. Kirichenko, and B.S. Luk'yznchuk, Russian Chemical Reviews, 62, 223, (1993).
[2] D. Banerle, Cemical Processing with lasers (Springer Series in Materials Sciences), Berlin, Springer, v.1, 1986.
[3] P.B. Kargl, R. Kullmer, and D. Banerle, Appl. Phys. A, 57, 175, (1993).
[4] P.B. Kargl, R. Kullmer, and D. Banerle, Appl. Phys. A, 57, 577, (1993).
[5] N. Kirichenko, Y. Khavin, and N. Arnold, Appl. Surface Sci., 93, 359, (1996).
[6] N. Kirichenko, K. Piglmayer, and D. Banerle, Appl. Phys. A, 61, 495, (1996).
[7] N. Arnold, E. Thor, N. Kirichenko, and D. Bauerle, Appl. Phys. A, 62, 503, (1996).
[8] Z. Toth, P. Kargl, C. Crivas, K. Pigmayer, T. Szorenyi, and D. Banerle, Appl. Phys. B, 54, 189, (1992).