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Figure 1

Figure 1: Figure 1

Abstract**Full Text**

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PHYSICS

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ON THE POSSIBLE INFLUENCE OF THE GAS CONTENT IN METALS ON THE ZONE AFFECTED BY A LASER BEAM

The action of a laser beam on metallic materials leads to their heating, melting, or the removal of part of the material from the affected zone (ejection of the liquid phase under the action of recoil vapor pressure ⁽¹⁾, surface evaporation ^(2,3), the mechanism of melting–washing out ⁽⁴⁾). The development of the indicated processes of material removal occurs at different radiation intensities q ; however, it is necessary that the value of q exceed a certain critical value (for most metals 10^5 – 10^6 W/cm²).

In welding metals with a laser beam, ejection can impede the production of a high-quality welded joint. At the same time, it should be noted that when part of the material is removed or displaced toward the edges of the molten-metal pool, the heat source is “deepened,” and in a number of cases this promotes the production of deep penetration.

The presence of a liquid phase, and taking it into account in analyzing the processes of heating by a laser beam, can have a noticeable influence on the kinetics of development of the treatment zone. From the moment the melting zone forms, the laser pulse interacts with the metallic liquid, which can be superheated to considerable temperatures as a consequence of the increase in the boiling temperature caused by the recoil pressure during evaporation. Significant superheating of the liquid layer can lead to boiling and the subsequent removal of the liquid phase, which may have an explosive character.

Fig. 1. Dependence of the depth of the crater on the pulse energy for samples of copper of different grades. *a* –cathode, *b* –vacuum-melted, *v* –as supplied, *g* –anode, *d* –black, *e* –porous.

The phenomenon of boiling of a gas-saturated liquid under the action of a laser pulse of duration 10^{-3} s was noted, for example, in ⁽⁵⁾. In ⁽³⁾, the role of

volumetric vapor formation was estimated for the case of metals in comparison with purely surface evaporation. These estimates, relating to ideal materials, showed that volumetric vapor formation at the superheats attained plays a small role in comparison with purely surface evaporation.

However, the presence in real metals of dissolved gases or impurities that can play the role of “artificial” (not spontaneous) nuclei for the boiling process is a factor facilitating boiling of the liquid phase at relatively small superheats in comparison with ideal metals.

The aim of the present work is to investigate the influence of some of the factors indicated above (degree of purity of the material, gas content, porosity) on the character and dimensions of the zone of material treatment by a laser beam. The work was carried out on a GOS-30 laser installation with neodymium glass (free-generation mode, pulse duration 1 msec). Samples of copper of various grades were investigated: cathode, anode, black, vacuum-remelted, in the as-delivered state, and also porous copper (porosity 28.4 and 36.8%). The treatment regimes (energy per pulse, focusing conditions) were selected so that in one case melting of the surface occurred (without noticeable evaporation), while in the other a crater was formed. In the work a lens with $f = 25$ cm was used. The sample was placed at a distance of 23 cm from the lens (melting regime) and at the focus of the lens. The energy per pulse, measured with an IEK-1 calorimeter, varied from 2 to 7 J (to obtain an energy below 3 J, a UFS-1 light filter with 18.5% transmission was used). At a pulse energy of about 2 J, which under our conditions corresponds to a power density of 10^6 W/cm², molten zones with separate small craters, caused by the action of individual peaks of the pulse, are formed on the surfaces of cathode and vacuum copper samples. In all other cases craters of different depths are formed: the smallest in copper in the as-delivered state, the largest in porous copper (Fig. 1). It should be noted that the character of the treatment zone in samples of porous copper differs noticeably from the treatment zone of monolithic samples at all power densities. Thus, with the value of the pulse energy preserved, but at a lower power density obtained by defocusing the beam, no noticeable removal of molten material was observed in all cases. However, the diameter of the melting zone in porous copper exceeded by one and a half to two times the zone diameter in samples of anode, vacuum, and as-delivered copper (0.89-0.93 mm and 0.42-0.60 mm, respectively). In addition, characteristic of the melting of porous samples is the formation of deep “wells” in the molten zone (Fig. 2). The shape of the craters obtained on porous samples as the power density is increased also differs noticeably from the shape of craters in monolithic samples (Fig. 3).

Fig. 2. Melting zone in a porous copper sample

In the region of higher pulse energies (above 4 J), the difference in crater depths decreases somewhat (for example, for cathode copper and copper in the as-delivered state), but the basic regularity is preserved, i.e., the crater depths are maximal for porous and black copper and minimal for cathode and anode copper. From the graph in Fig. 1 it is evident that the character of the change

Figure 3

Figure 2: Figure 3

in crater depth as a function of pulse energy differs for different grades of copper. The greatest scatter of points is observed for black copper, which can apparently be explained by greater inhomogeneity of the samples (large pores, inclusions, etc., were present in the bulk of the material).

Quantitative spectral analysis of some copper samples showed that, with respect to the content of a number of impurities, they differ little from one another. A substantial difference is observed in the content of lead (less than 0.005% in cathode and anode copper and about 1.0% in black copper), nickel (less than 0.08% in cathode and anode copper and 1.0% in black copper), and oxygen (0.005% in cathode copper, 0.05% in anode copper, and approximately 0.8% in black copper).

To interpret the results obtained, estimates were made of the possible depth of craters in copper using relations for quasi-stationary evaporation (2) and a one-dimensional gas-dynamic model of material destruction (3):

$$v_{(1)} = q_0/\rho_0(L + cT^*), \quad (1)$$

where q_0 is the specific power averaged over the pulse duration, W/cm^2 ; L is the specific heat of evaporation, J/g ; ρ_0 is the density of the condensed substance, g/cm^3 ; c is the specific heat capacity, $\text{J}/\text{g} \cdot \text{deg}$; T^* is the surface temperature of the material for quasi-stationary evaporation;

$$v_{(2)} = 8q_0(\kappa - 1)/\rho_0L(\kappa + 1), \quad (2)$$

where κ is the adiabatic exponent, taken in our case to be equal to 5/3. Substituting into (1) and (2) the values $\rho_0 = 8.7 \text{ g}/\text{cm}^3$, $L = 4.8 \cdot 10^3 \text{ J}/\text{g}$, we obtain $v_{(1)} \approx v_{(2)} = 50 \text{ cm}/\text{s}$. Hence the maximum crater depth can be found from the relation

$$h = v(\tau - \tau_1 - \tau_2), \quad (3)$$

where τ_1 is the delay time required to heat the material to the boiling point at normal pressure, when surface evaporation begins to play an essential role in the kinetics of metal destruction; τ_2 is the time required to attain the quasi-stationary evaporation regime.

Fig. 3. *a*—section of a crater in an anode-copper sample; *b*—section of a crater in a porous-copper sample (porosity 28.4%)

For $q_0 = 10^6$ W/cm², $\tau_1 = 0.8 \cdot 10^{-4}$ s, which is small in comparison with the pulse duration used in the experiment, $\tau = 10^{-3}$ s. It should also be noted that the quantities $v_{(1)}$ and $v_{(2)}$, calculated using relations (1) and (2), are reached practically only by the end of the pulse action, since the time for establishment of the quasi-stationary evaporation process $\tau_2 = 8a/v^2$ (2) is of the order of the radiation-pulse duration. Substituting into (3) the values $v = 50$ cm/s, $\tau_1 = 0.8 \cdot 10^{-4}$ s, $\tau_2 = 0.8 \cdot 10^{-3}$ s, we obtain $h = 0.1$ mm, which is substantially less than the crater depth attained

under the corresponding conditions in our experiments with copper. This conclusion is further strengthened if one takes into account that, in the estimates by (1), (2), and (3), the effect of reflection was neglected, which in the case of copper can reach large values.

Let us now estimate the maximum melting depth attained by the end of the pulse action, using the relation

$$t = \frac{2q_0}{\lambda} \sqrt{a\tau} \operatorname{ierfc} \frac{x}{2\sqrt{a\tau}}. \quad (4)$$

Substituting the values of the coefficients for copper, $\lambda = 0.935$ cal/cm · s · deg, $a = 1.0$ cm²/s, we obtain a melting depth $h = 0.31$ mm, which is much smaller than the crater depths observed experimentally.

The estimates obtained show that one-dimensional evaporation problems cannot describe the dynamics of crater development in a material containing impurities and gases. It should also be emphasized that the assumption of changes in the thermophysical coefficients due to the presence of impurities and, as a consequence, changes in the dimensions of the processing zone can be discarded on the grounds that the impurity content affects these properties only at low temperatures (6).

In light of the above, experiments with materials containing a large volume of gases, i.e., with powder-metallurgy materials, become of interest. Systematic studies of the action of a laser beam on such materials have not been carried out. In the literature there is only mention of such experiments in work (7). As was already stated above, in the case of porous specimens the crater depth increases sharply, and its shape also differs substantially from the crater shape in monolithic specimens. Apparently, when considering the mechanism of destruction in this case, one cannot ignore the possible transfer of radiation into porous specimens (the appearance of a radiative component of the thermal-conductivity coefficient), as well as a substantial decrease in mechanical strength.

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