MATEC Web of Conferences **61**, 01015 (2016) DOI: 10.1051/matecconf/20166101015
APOP2016

States and Properties of Metallic Systems at a Threshold Breakdown of the Through Holes Under Power Laser Action. Threshold Breakdown of Through Holes in Metal Foils by Powerful Laser Radiation (Part 1)

Kalashnikov E[1a], Kantor M[2]. Bugayev A[3]., Kouprienko D[2]., Chikiryaka A[2].

[1] Moscow Region State University, Moscow, Russia
[2] Ioffe Physical Technical Institute, RAS, S.-Petersburg, Russia
[3] Applied Research Center Old Dominion University, VA 23606 USA

Abstract. Energy of threshold breakdown of through holes in metal foils of different thicknesses by powerful laser radiation is investigated experimentally. Properties of foil matter at "liquid metal-gas" phase transition are revealed. One of controlled parameters of the threshold breakdown is the outlet on the shady side of the target. The threshold breakdown hole is outlet of hole for a given foil thickness when further decrease of energy is not able to create.

1 Introduction

Affecting of powerful laser irradiation on metallic (dielectric and semiconductor) targets leads to formation of craters and holes, moving away of substance from a target - to the ablation [1-12]. The special role are here playing the different thermodynamic states - "solid, liquid, gas, plasma" in which substance consistently goes across.

To control such possible states and transition between them it is necessary to know the amount of energy absorbed by a substance. As a rule, it, last, presents the greatest problem in the tasks of interaction of powerful laser radiation with a substance because as for this purpose it is necessary to know at least an absorption coefficient (which, in turn, depends on a temperature and, accordingly, the state of substance). Practically, the measuring of the temperature of the states of substance during process of experiment is not succeeded. At the best, a model of thermal problem is considered [2-4, 7, 10, 12] with respect to surface and volume temperature distribution at taking into account brought energy. After that, the temperature distribution is compared with experimental results. At low intensities, when perturbation of electronic subsystem is small, such "thermal approach" allows to analyze more complex problems [13]. Also, characteristics, which show that a substance is in a critical state (there is "liquid metal-gas" transition at the critical temperature), are also absent. Nevertheless, at certain cases it is possible to specify characteristics showing closeness to the critical temperature [9] and even to fix the borders of spinodal in a transition "liquid-gas" [3].

Aim of this part of the work is to find experimental characteristics of substance at interaction with laser radiation, which allow to define the presence of "liquid metal-gas" second order phase transition.

The work is devoted to experimental research of laser-induced breakdown threshold holes in metallic foils under act of single-pulse with minimum energy, which would be enough to provide minimum possible hole through in foil of the set thickness. Such statement of problem defined requirements to the radiative device – pulse duration and power of radiation.

2 Scheme of experiment

A ruby laser served as source of irradiation with the wavelength $\lambda = 694\ nm$ in the mode of free generation. An impulse duration was fixed: $\tau = 1ms$. The beam of laser was focused by a short-focus lens (with focal distance of $F = 20\ mm$) on the surface of metallic target in a spot by the diameter of $f = 50\ \mu m$. The laser radiation power density in experiments was varied within the bounds of $10^6 \div 10^8\ W/cm^2$, that, as is generally known [8,10], lies within bounds of transparency of evaporant. To register upraise of hole a detector in a camera-obscure was placed behind a target. Radiation power was registered by another photodetector. The detectors worked in the mode of synchronization with a laser. A delay time was measured during laser-induced breakdown threshold holes. Power of radiation was fixed and registered. Variation of this power (for maintenance of unchanging temporal structure of pulse) carry out by the graduated color filters. Laser-induced threshold holes of foils were studied in the atmosphere of air at normal pressure and room temperature.

Metallic foils were prepared from a copper (with 99,999-weight % of main component), stainless steel, niobium and aluminum. The prepared holes of foils were

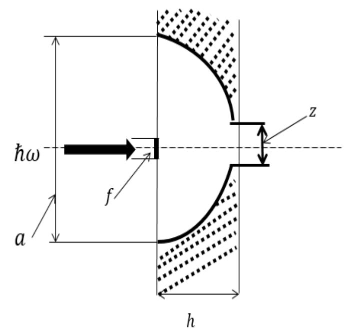
[a] ekevkalashnikov1@gmail.com

studied under an optical and electron microscopes. In order to calculate mass of holes a longitudinal (along the axis of holes) micro sections were prepared.

3 Results

Results of experiments are presented on fig.1 - 6. At the small thicknesses of foils, *Fig.1a*. The threshold holes have a cap-like form, by a large diameter turned to the falling radiation. At the increase of thickness of foil the form of the threshold holes is changing and takes

a)



b)

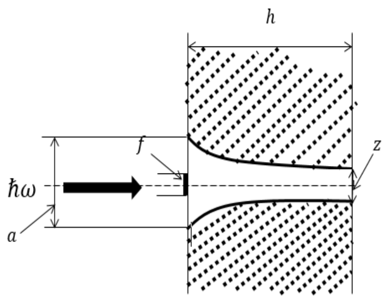


Fig.1. Form of the through threshold hole (along the axis of hole) for thin (a) and thick (b) foils; *a* and *z* is a entrance and outlet diameter of hole, accordingly, *h* is a target thickness, *f* is a focal spot

shape of the prelate truncated cone with hyperbola-like line formative, *Fig.1b*. - In thin foils the energy of radiation is spent on formation of large surface of input hole, substantially exceeding the size of focal spot. In thick foils, the size of input hole exceeds the size of focal spot not very. Size z of output dimeter (a shadow side) of threshold holes is different too. Fig.2 demonstrates the values of diameter, z, of conical holes measured (on a shadow side) on an exit.

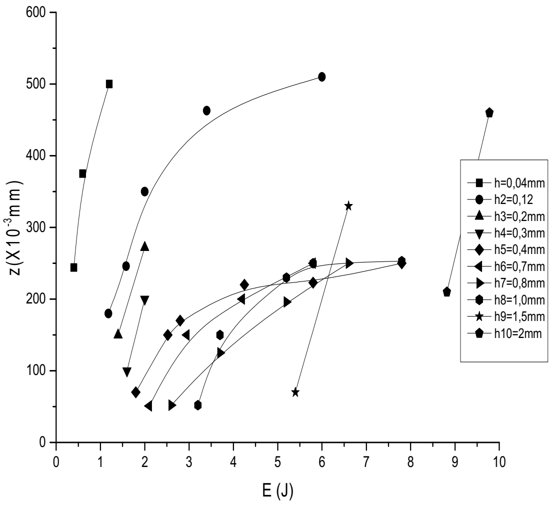


Fig.2. Outlet diameter of through hole vs energy of falling radiations for the different thicknesses of *h* foils.

Dependence of $z = z(E)$ on fig.2 is similar to a form dependence of entrance diameter of the deep craters with respect to energy of falling radiation [1, 8, 10]. But a main feature of these dependences (*Fig.2*) consists of minima of $z(E)$ of exit holes. So each minimum exit hole (threshold hole for each thick of foil) corresponds to threshold energy. Subsequent decreasing of energy does not lead to creation of hole through, although a craters and deep small holes appear.

Diameter of exit hole, z, at minimum possible energy, below which hole does not push (*Fig.2*) through is designated the threshold diameter of Φ corresponding to threshold energy E_p. Circumflex of threshold diameters of $z\ (E = E_p) = \Phi$ against energies of thresholdings resulted on *Fig.3*.

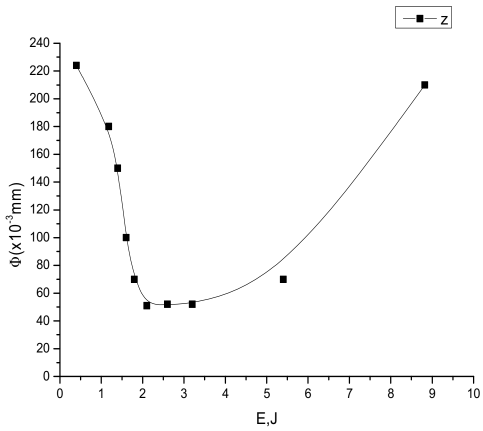


Fig.3. Dependence of threshold diameter of output diameter Φ on threshold energy of E_p for a copper.

On fig.4 dependence over of threshold diameter is brought on the thickness of foil, $\Phi = \Phi\ (h)$ for a copper and stainless steel, having different to heat conductivity.

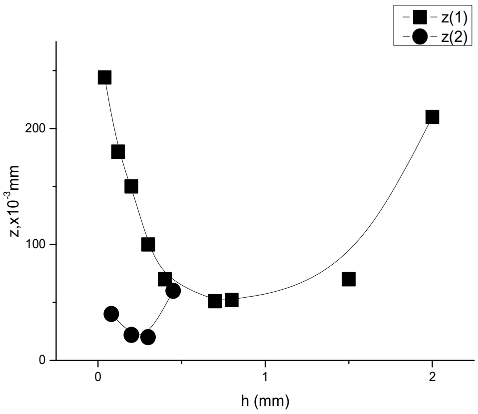


Fig.4. Diameter of the threshold hole depending on the thickness of foil: for a copper, z (1) = Φ1, and for stainless steel, z (2) = Φ2.

Finally, relation of threshold energy, E_p , absorbed by threshold holes with respect to their masses, E_p/m, versus falling energy of radiation of E has pic-like behavior. If it could be possible to express E as absolute temperature, T, the relation $(E_p/m)/E$, would be similar to heat capacity of C_p. Behavior of C_p vs temperature at second order phase transition has λ-like character [14]. So, the relation, $(E_p/m)/E$, could be served as the index of second order phase transition of "*liquid metal-gas*" one.

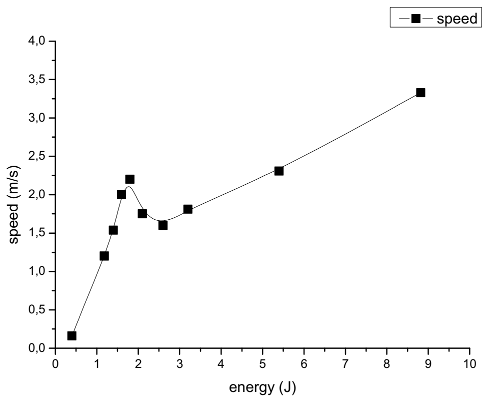


Fig.5. Speed of moving of "gas-liquid-solid" sandwich vs threshold energy of breakdown.

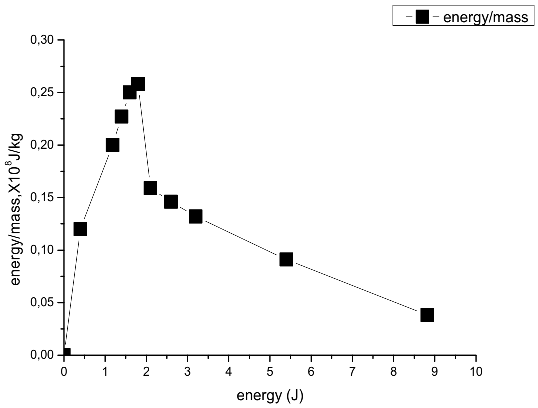


Fig.6. Relation of the threshold energy absorbed by mass of threshold hole to falling on a target of energy of radiation.

4 Discussion

Stream of radiation $10^8 \div 10^{10}$ W/cm^2 provides, as is generally known, mode of the developed evaporation. Mode of heat conductivity here, though eliminated, but determines the that minimum thickness of layer of $l \sim (\chi\tau)^{1/2}$, that has time to transform into a liquid and warmed up in times of action of impulse $\tau \sim 10^{-3}$ s to the high temperature of evaporation of T (here χ is a heat conductivity). However, at the sharp focusing of ray [8, 10], radius of the exposed to rays ground: $r_o \leq l$. Thermal losses become substantial and, in final analysis, determine the terms of forming of the through opening. It appears thus, that $l \sim h$ and condition of semi-infinite model $(h \geq 3\ (\chi\tau)^{1/2})$, [8, 10]) is not supported. In that case, using the traditional analysis of heat conductivity problem, we carry out the quality analysis of dispersion of falling energy. The appearing temperature drop, ΔT, between the lighted and shadow sides of target and between the center of the lighted spot and its periphery causes moving of front of moving away of substance "along" the (negative) gradient of temperature. Thermal losses through a surface normal to the falling ray (through front) equal to $P_h = \lambda \cdot \pi \cdot r^2 \cdot \Delta T/h$ and the same through flank surface (truncated cone, approximately, cylinder) equal to $P_r = \lambda \cdot \pi \cdot r^2 \cdot \Delta T/r$. The relation of these components

$$R = P_h / P_r = r^2/h^2$$

connects radius, r, with height, h, of threshold hole. It means that

(*a*) if $R \ll 1$, then all energy is spent on formation of hole.

(*b*) if $R \gg 1$, that all energy of impulse is spent on formation of area of surface turned of to the falling radiation.

Radius of hole arising up during of laser impulse with energy near its threshold value can be estimated through next relation

$$r^2 = \lambda \cdot \tau/\rho \cdot c$$

where λ is heat conductivity, ρ – density, c – heat capacity. In that case, relation of R can be written as $R = \lambda \cdot \tau/2\rho \cdot c \cdot h^2$ and boundary between cases (*a*) and (*b*), $R = 1$, determines suitable thickness of foil

$$h = (\lambda \cdot \tau/2\rho \cdot c)^{1/2}$$

As a result, the thickness of copper foil equals to $h_{Cu} = 0{,}25\sqrt{\tau}$ *mm* and the same for stainless steel (st_st) foil is $h_{st\_st} = 0{,}09\ \sqrt{\tau}$ *mm*. It leads to $h_{Cu} / h_{st\_st} \approx 3$. This situation is well confirmed by an experiment, fig. 4: relationship of thicknesses h_{Cu} / h_{st_st} with the minimum through threshold holes is the same. Such situation supposes that process of motion of some complex formation of «gas-liquid-solid» through thickness of foil are fully controlled by heat conductivity of solid. . It means that creation of liquid metal on solid with next transformation into gas state takes place during the process. In this way, sandwich-like formation (solid-liquid-saturated gas) moves through thick of foil. It is impotent to notice a speed of the formation,

$V = V(E)$, has specific zigzag at max of $(E_p/m)/E$. It means that after the achievement of values of energies at that a peak appears in dependence of $(E_p/m)/E$ fig.6, there is a critical condition corresponding to the transition "liquid metal-gas"[14]. A liquid metal achieved at a temperature equal or near to the critical temperature. Therefore, that "front" of "liquid-gas" begins to move in an opposite side. A liquid, quickly broadening, loses the border of division "liquid-gas" and arrives at a critical condition.

Two «slowest» processes control heating, phase transformations and motion of such sandwich. First of them is due electron-phonon interaction and is characterized by time of changing lattice temperature $\tau_1 \sim 10^{-10} s$ [15]. Second "slowest" process is connected with compression and decompression by the way of joining of atom to arising condensate (or to the exit from an arising up compression) of atoms. This process is characterized by time of order $\tau_2 = (a/v) \sim 10^{-14} s$, where a is interatomic distance, v is speed of sound. It means that originated liquid will reach equilibrium state at certain temperature faster then will be cooled due to electron-phonon interaction. By the way, it is possible to suppose that at each value of threshold energy E_p , of laser field and at certain thickness, h, of foil in threshold hole, a certain equilibrium temperature will be set and exit threshold hole z will correspond to equilibrium temperature $z = z(T)$. Dependences of z = z (h) for investigated metals are similar. It means processes taking place at the threshold holes of foils on different metals are similar too.

Thus, it is possible to suppose that all set of descriptions of threshold holes at minimum possible (threshold) energy in an impulse largely caused by processes taking place at the critical and near to them parameters of the state of substance

5 Conclusion

A laser-induced threshold holes of foils finds out new characteristics of metals at its reaction on influence of laser radiation:

1) diameter of exit threshold hole, Φ = Φ(Ep), depending on energy of falling radiations Ep for the different thicknesses of h foils has the clearly expressed minimum. The characteristic, Φ = Φ(Ep), on the form remains unchanging for substances with the different heat conductivity- from badly conducting materials to the metals with good heat conductivity

2) relation (Ep/m)/E is similar to heat capacity of Cp at phase transition of the second order "liquid metal-gas". It shows extremum behavior versus energy and corresponds to a minimum of description = (Ep). So (Ep/m)/E could be served as the index of second order phase transition of "liquid metal-gas" one.

3) energy absorbed by threshold hole volume is fully controlled

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