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Features of the keyhole evolution during deep penetration of metals by laser radiation

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The paper presents the results of fast detection of the keyhole formation in titanium under point exposure to laser radiation. The fact has been established that the keyhole evolution ends with a collapse even before the cessation of the action (switching off) of the continuous laser radiation.

Keywords: deep penetration, keyhole, collapse, laser radiation.

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When metals are exposed to laser radiation in the process range of intensity ($\sim 1\,\mathrm{MW/cm^2}$), the effect is observed of deep-penetration with formation of a hollow keyhole through which the laser radiation penetrates into the metal bulk providing even larger penetration depth. This effect is exploited in laser welding of large-thickness metals. The interest in this effect has grown in recent years due to intense development of an additive manufacturing technology involving the technique of laser power bed fusion (LPBF) [1]. To simulate those manufacturing technologies it is necessary to possess reliable and experimentally validated knowledge of the keyhole formation mechanism. In literature, two possible mechanisms of the keyhole formation are considered. The first one is commonly known, it suggests the melt displacement by the recoil pressure of vapors expanding from the molten surface (ablation pressure) [2]. The ablation mechanism may dominate in the keyhole mode if the energy-consuming evaporation is sufficiently intense, and the vapor recoil pressure is sufficiently high to mechanically maintain the keyhole but with insignificant power consumption for evaporation ($\sim 1\%$ of the absorbed power as per the measurements of [3]). The estimates obtained do not confirm simultaneous fulfillment of these conflicting conditions [4]. The other mechanism is related with the temperature dependence of the melt surface tension, which gives rise to tangentional thermocapillary forces and thermocapillary flowing of the molten metal (thermocapillary effect) when the surface is heated nonuniformly [5,6]. The keyhole formation by the thermocapillary forces needs the melt flowing from the center of the irradiation spot towards its periphery (a negative surface tension temperature coefficient $d\sigma(T)/dT < 0$) with the retention of the shear flow structure during the keyhole formation. To meet condition $d\sigma(T)/dT < 0$, the melt temperature should exceed the point of $d\sigma(T)/dT$ sign inversion which depends on the impurity content in the metal and is typically several hundred degrees higher than the melting point [7]. This condition is guaranteed in the keyhole mode since the cavity surface temperature is close to the boiling temperature [8]. The thermocapillary flow shear structure characteristic of the initial melting stage persists during the keyhole formation provided the radiation power reaches its threshold (at the preset spot size) of the transition to the deep-penetration mode [9].

The ablation pressure mechanism enables simulation of relatively simple process tasks but is accompanied by significant distortions of hydrodynamic parameters and vapor flow characteristics [4], which restricts modeling of complex hydrodynamic processes of defect formation. Some researchers explain this by inadequateness of the available knowledge on the process physics [10–12] and notice the absence of experimental evidence of the ablation pressure mechanism domination within the process range of intensity [13], which suggests the existence of other possible mechanisms. The goal of this paper is revealing the predominant melt transport mechanism in the process of the keyhole formation in metal under the point exposure to continuous laser radiation. The conclusion about the dominating melt transport mechanism can be made based on specific features of the keyhole evolution under the point and long-term exposure to continuous radiation.

Domination of the vapor ablation pressure mechanism stipulates such a keyhole evolution during the point welding that the keyhole depth reaches saturation and persists at this level with insignificant fluctuations for an arbitrary time of the laser exposure (Fig. 1), which is confirmed by demonstration experiments with liquids [2]. Intense evaporation during either point or long-term exposure to continuous laser radiation should ensure, due to high vapor recoil pressure, the keyhole mechanical maintenance of the same duration. In this case, the keyhole may disappear only after stopping the irradiation.

The thermocapillary mechanism stipulates another type of the keyhole evolution [5] specifically characterized by tangential direction of surface tension forces arising in

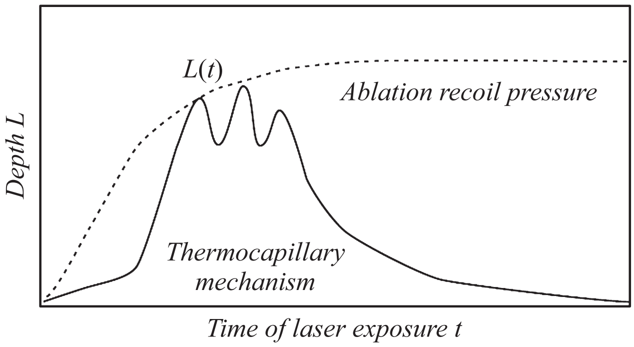

Figure 1. The keyhole evolution to depth $L(t)$ for different dominating formation mechanisms (thermocapillary or vapor ablation pressure).

case of nonuniform laser heating. These thermocapillary forces make the melt move and are counterbalanced by viscous forces. If the power threshold (P_{th}) is exceeded, the emerging thermocapillary spreading of melt from the irradiation spot center to its periphery is accompanied by a considerable surface deformation and formation of a deep keyhole. This is promoted by an increase in effective radiation absorption because of multiple rereflections within the keyhole. The main role is played in this case by the interaction between phase interfaces with participation of the viscous sublayer. This interaction creates hydrodynamic conditions for the steady process of keyhole formation for equal values of melting front speed V_M and surface deformation rate V_S $(V_M = V_S)$ [5,6]. The termination of the steady process of the keyhole formation (reaching the limiting depth) is the beginning of the thermocapillary recirculation (Marangoni convection) with the closure of streamlines. The keyhole becomes filled with flow and disappears. This collapse is a distinctive feature of the evolution in the case of thermocapillary mechanism of the keyhole formation, which is confirmed by a model experiment with paraffin melting [5]. The possibility of the thermocapillary mechanism predominant role in metal welding is also confirmed by estimates obtained in [4,6,9,14,15]. The authors of [16] showed by numerical simulation of the aluminum laser drilling that the relative influence of the ablation recoil pressure and thermocapillary effect on the cavity depth depends on the heating temperature, the first one dominating when the heating temperature significantly exceeds the boiling point, while the other dominates at the temperatures close to the boiling point. It appeared that supplementing the ablation pressure to the thermocapillary effect near the boiling point increases the cavity depth only by $\sim 10\%$. According to measurements obtained in [8], the melt temperature in the keyhole reaches the saturation near the boiling point, thus the [16] results may be regarded as the evidence of the thermocapillary mechanism domination in deep penetration. Distinctive features of the mechanisms define the keyhole evolution characterized by either the presence or the absence of the terminating collapse in the case of either thermocapillary or ablation mechanism domination (Fig. 1). This makes it possible to experimentally determine the dominating mechanism of the keyhole formation from the character of its evolution in a metal sample (from the presence or absence of collapse under irradiation). Just this experiment was the goal of this study.

To visualize the welding process, a sample of the „sandwich" type consisting of titanium and sitall plates tightly pressed together was used (Fig. 2). The detection was performed through the optically transparent sitall with the shooting frequency of 1000 fps. The continuous radiation of the CO_2 laser 1.5 kW in power was focused on titanium near the plate joint. Titanium was protected against atmospheric gases by feeding helium.

The radiation was focused by using the condition of forming the keyhole via the thermocapillary mechanism [9,14] having for titanium in the SI system the following form: $AP_{th} \approx 1.6 \cdot 10^7 d^{4/3}$ (where A is the effective absorption in the keyhole, d is the focusing spot diameter). Multiple rereflections in the keyhole keeps absorption A within the range of 0.6 to 0.9 [17]. When $A = 0.6{-}0.9$ and laser power is 1.5 kW, transition to the keyhole mode is possible if condition $d < 0.82{-}0.92$ mm is fulfilled which is true in radiation focusing. After starting the laser irradiation, at the stage of the keyhole growth, images of its thermal wakes were detected, which were created by metal incandescence at very high temperatures (Fig. 2). The metal glowing in the visible spectrum region begins at the temperature of $530{-}580^\circ$C and has the dazzling white radiant heat color at the temperature of $1250{-}1300^\circ$C close to the titanium melting point 1400°C. The maximal depth of the heat wake at the time of 0.19 s (the third photo in Fig. 2) is 4.5 mm and significantly exceeds its width, which indicates the keyhole formation. On reaching the limiting depth, disappearance of the keyhole heat wake is observed over the total height simultaneously and results from right-to-left motion of the fast darkening wave (like a „shutter"motion). The image disappearance excluded the line $L(t)$ extension in Fig. 2, which is conditionally marked with a shaded area. Evidently, such a character of the image disappearance may be caused by formation of helical flows in the keyhole overflowing. The penetration detection continued for a time (~ 2 s) sufficiently long to make sure that the keyhole cannot be formed again.

Pay attention to the experiments of [1] in which the keyhole evolution in the titanium alloy under the point laser action was detected via high-speed synchronous (x-ray) visualization. However, tracing of the evolution of the keyhole depth $L(t)$ stops suddenly without explaining the reasons on the completion of the keyhole growth stage and the following stage of fluctuations development in the keyhole. The premature termination of tracing the keyhole depth variation with time $L(t)$ observed in [1] is demonstrated for all the ten presented experiments with varying laser power and focusing spot diameter and may be also related with the keyhole disappearance due to its collapse ignored by the authors.

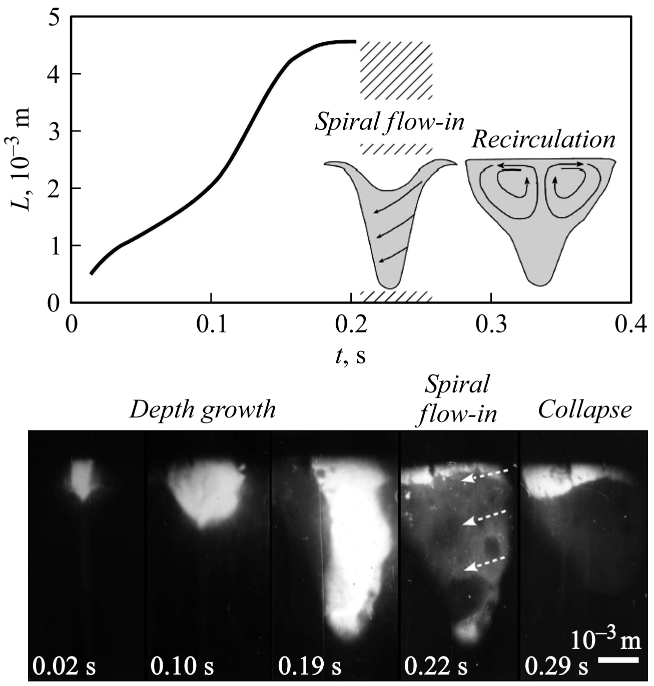

Figure 2. Visualization of the keyhole heat wake in titanium under long-term point exposure to continuous CO_2 laser radiation 1.5 kW in power. The keyhole evolution terminates with its disappearance (collapse).

Hence, the keyhole collapse we have revealed does not contradict the experimental data of [1] but supplements it. We pay attention to the fact that the keyhole evolution in metal under both the point and long-term exposure to laser radiation enables experimental defining of the dominating mechanism of the keyhole formation. Being considered jointly with data of [1], the results of this experiment allow assuming that the keyhole evolution in metal (under the point and long-term exposure to laser radiation) is terminated by collapsing under the action of radiation, which indicates the thermocapillary mechanism of the keyhole formation.

Conflict of interests

The authors declare that they have no conflict of interests.

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