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Drilling and cutting of thin metal plates in water with radiation of a repetitively pulsed Nd : YAG laser

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Abstract. **The conditions of drilling and cutting of 0.15-mm-thick titanium and stainless steel plates in water with the radiation of a repetitively pulsed Nd : YAG laser having the mean power up to 30 W are studied experimentally in the absence of water and gas jets. Dependences of the maximal cutting speed in water on the radiation power are obtained, the cutting efficiency is determined, and the comparison with the conditions of drilling and cutting of plates in air is carried out.**

Keywords: *laser cutting and welding, radiation power, heating, heat emission, efficiency.*

1. Introduction

Laser cutting and welding of metal constructions in water becomes one of promising areas in the development of laser thermal technology. Fibre optics allows one to easily transport radiation to the interaction site and to perform such technological operations, as, e.g., cutting of ship hulls for future utilisation or current repair.

To increase the efficiency of laser cutting and welding of metals in water and to improve the weld and cut quality, use is usually made of water or gas jets, targeted at the site of the focal spot localisation on the metal surface. The jet effect leads either to elimination of the beam defocusing due to refraction on gas bubbles by removing the bubbles from the interaction volume (water jet) [1], or to creation of a locally dried volume (gas jet) [2–4]. In the case of the local drying with a gas jet, the efficiency of laser cutting and welding in water is rather high. Thus, in Refs [2–4] these operations were performed with ~10-mm-thick metal plates using cw radiation transmitted through an optical fibre from a 4-kW Nd : YAG laser or 7-kW oxygen – iodine laser.

If supplying a water or gas stream to the interaction site is not reasonable or hard to achieve, one has to perform laser cutting or welding of metal constructions in water in the absence of the jet. In this case, due to the increase in the local heat extraction from the constructions submerged in water, one should expect the growth of energy consumption as compared with processing in the air.

The goal of the present paper is to study experimentally the conditions of in-water laser drilling and cutting of 0.15-mm-thick plates made of titanium or stainless steel with the radiation of a repetitively pulsed Nd : YAG laser having the mean output power up to 30 W and to compare the obtained results with those of drilling and cutting in air in the absence of water environment.

2. Experiment

Metal plates made of titanium and stainless steel (X18H10T) with the dimensions 1.5×3 cm and thickness $h = 0.13$ and 0.15 mm, respectively, were placed vertically when irradiated in air and horizontally when irradiated in water. Their surface was oriented perpendicular to the direction of the light propagation. It was found that the conditions of drilling and cutting in the air do not depend on the plate orientation. The choice of the vertical position is explained by the convenience of determining the drilling time. The change in the output laser beam propagation direction from horizontal to vertical for processing in water was implemented using a fold mirror, mounted after the focusing lens following the beam path. The plates were fixed in a metal cuvette filled with distilled water. The water layer thickness, covering the front surface of the plate facing the laser beam, was ~2 mm, and the water layer thickness adjacent to the back side of the plate was 10 mm.

A repetitively pulsed Nd : YAG laser with the FWHM pulse duration $\tau = 130$ μs and variable pulse repetition rate and pump power was used as a source of radiation. The size d of the focal spot of multimode radiation, focused onto the plate surface, depended on the conditions of laser operation and, for the constant focal length of the focusing lens, was equal to 0.22 or 0.3 mm, which corresponds to the condition of irradiation of thermally thin plates ($d/h > 1$).

The time of perforation in the course of irradiation of a fixed plate in air was measured at the moment of appearance of bright sparks from the back side of the plate, and in water it was found from posterior visual investigation of the array of radiation-affected sites, corresponding to different exposure times, by means of an optical microscope. In both cases the accuracy of time measurement was ±0.5 s. The visualisation method was applied also for distinguishing between the different characters of the interaction site that appear when moving the target, namely, surface melting or reach-through melting of the plate, perforated cut and continuous cut. The velocity v of the sample movement did not exceed 0.2 mm s^{-1} and could be varied with the accuracy of 0.005 mm s^{-1}. During the irradiation in water the plate was fixed in the cuvette and was moved together with it.

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Under irradiation in water of both motionless and moving plates practically in all exposure regimes, one could observe intense boiling process in the water volume adjacent to the focal spot, accompanied by the outcome of gas bubbles to the surface and their symmetric propagation in water in the radial direction off the beam axis. To avoid the vapour condensation on the surface of the fold mirror and the change in radiation focusing conditions, the vertically directed vapour flow was blown aside using an auxiliary horizontal jet of air that did not interact with the water surface.

3. Results and discussion

3.1. Drilling of plates

Figure 1 plots the time t_0 of getting a through perforation in the titanium and stainless steel plates at $v = 0$ versus the mean power P of the laser radiation, focused onto the surface of the plates. Because of the small thickness of the water layer ($\sim$2 mm) from the front side of the plate, the absorption of laser radiation in water could be neglected [5]. When the plates are irradiated in air, an optical discharge arises at the surface. The absorption of laser radiation in the discharge plasma was also neglected because of the small absorption coefficient [6] and small (not greater than 10 mm) length of the discharge along the beam. Therefore, the power P in Fig. 1 (and all the figures below) is equal to the output power of the laser, attenuated by the absorption in the focusing lens or in the lens and the fold mirror. As follows from Fig. 1, at a fixed power the drilling time t_0 in air increases with increasing repetition rate f [curves (*1*, *2*)], for the stainless steel plate, the drilling time is greater than for the titanium one [curves (*2*, *3*)], and in water the drilling time is considerably longer than in air [curves (*2*, *4*)].

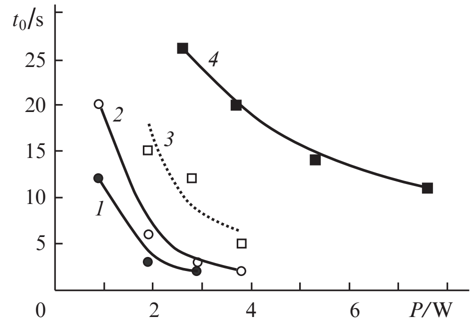

Figure 1. The time of the hole formation t_0 versus the mean radiation power P for drilling of plates in air (*1–3*) and in water (*4*) for titanium (*1*, *2*, *4*) and stainless steel (*3*). The focal spot diameter $d = 0.22$ mm, the pulse repetition rate $f = 50$ (*1*) and 100 Hz (*2–4*).

In the case of drilling in air, the noticed features are related to a decrease in the metal vapour pressure under lowering the fluctuating temperature δT in the near-surface layer of the plate [7] with increasing f and the heat conductivity coefficient of stainless steel, as compared to titanium having nearly the same plate thickness, approximately equal radiation absorption coefficient and unchanged mean power: $\delta T = 2AP/(fs\tau\lambda)(\chi t_1/\pi)^{1/2}$, $t_1 < \tau$ (here A is the coefficient of radiation absorption, λ is the heat conductivity coefficient, $s = \pi d^2/4$ is the focal spot area, χ is the thermal diffusivity).

The increase in t_0 when drilling in water may be explained by the increase in heat extraction in water. For this purpose let us compare two channels of laser radiation power loss, namely, the heat release from two opposite surface regions of the plate having the area S, heated up to nearly the same mean temperature ΔT, $Q_1 \approx 2\alpha S\Delta T$ (here α is the heat-transfer coefficient), and the transverse heat conduction $Q_2 \approx 2\pi h\lambda\Delta T$, where h is the plate thickness. We neglect the thermal wavelength $l \sim (\chi\tau)^{1/2} \approx 2\times10^{-3}$ cm for titanium in comparison with the radius of the focal spot and assume $S \approx s$. Under these assumptions, we obtain $Q_1/Q_2 \approx \alpha d^2/(4\lambda h)$. For a plate in air, the heat-transfer coefficient may be estimated using the expression $\alpha = \lambda_a(g/(d\eta^2))^{1/4}$ [8] (here λ_a, η are the heat-transfer coefficient and the kinematic viscosity coefficient for air, respectively; g is the free fall acceleration), then we get $Q_1/Q_2 \approx 3\times10^{-3}$. For film boiling in water, the heat release is also small ($Q_1/Q_2 \sim 10^{-2}$), in spite of almost triple increase in the heat-transfer coefficient [9]. One can suppose that the considerable increase in the plate drilling time in water compared with that in air occurs due to the mixed boiling regime, namely, the film boiling under the action of a radiation pulse, when the fluctuating temperature exceeds the critical temperature for the film boiling beginning, and the bubble boiling during the pause between the pulses, when the mean temperature is smaller than δT. The heat-transfer coefficient for bubble boiling is considerably higher than for film boiling, particularly under the conditions of pulsed heating, when the bubbles, located on the surface, have no time to tear off the surface [10, 11]. The dynamics of the bubble motion under heating the surface with pulsed laser radiation, which is interesting from the point of view of changing the heat release, was studied, e.g., in Refs [11, 12]. To determine the mean heat-transfer coefficient in the case of the mixed boiling regime, supposed in these experiments, one has to perform special experimental and numerical studies. Hence, we can only note that the intense heat release in the case of bubble boiling during the pause between the pulses, alongside with the refraction of laser radiation by gas bubbles, can also cause a significant increase in the plate drilling time in water in comparison with that in air.

Under irradiation in water, the relief of the surface within the focal spot and the adjacent external area significantly differ from that under irradiation in air. At a moderate mean power of laser radiation we can trace the evolution of the relief through large enough temporal intervals.

In air the relief evolution is analogous to that described earlier (see, e.g., [13, 14]) and will not be discussed in detail here. Note only that after the formation of a hole, the growth of the diameter d_m of the rest peripheral part of the weld becomes slower, then stops, and finally d_m is only a little greater than the diameter of the hole, which becomes equal to the diameter d of the local spot [Fig. 2, curves (*1*, *2*)].

Under irradiation in water at the outer boundary of the thermal action site there is no characteristic swelling of solidified metal that appears in air due to thermocapillary convection. This may be associated with the action of the transverse pressure forces of water vapours in the supercritical state, which is much greater than the surface tension force. Instead of continuous weld in the periphery of the focal spot, a region appears consisting of droplets of solidified metal with the size $\sim$20 μm, uniformly distributed over the darker oxide film, and the diameter of this region d_d significantly exceeds d [Fig. 2, curve (*3*)]. The appearance of droplets may be caused by the fragmentation of the weld, pushed out with water

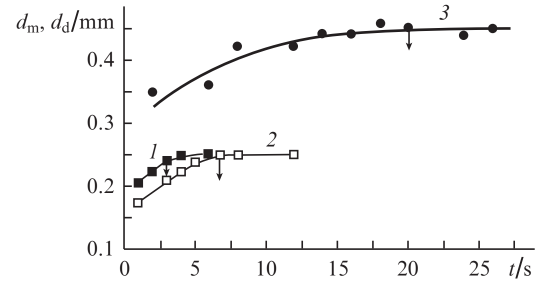

Figure 2. Dependences of the melt diameter d_m in the case of drilling in air (*1*, *2*) and of the region occupied by droplets d_d in the case of drilling in water (*3*) on the iradiation time t for titanium at $d = 0.22$ mm [$f = 50$ (*1*) and 100 (*2*, *3*) Hz and $P = 1.9$ (*1*, *2*) and 3.5 W (*3*)]. The arrows show the time of the hole formation.

vapours, at the boundary with the surrounding medium due to the development of Rayleigh–Taylor instability, exclusion of the fragments to the periphery by the transverse pressure of water vapours, followed by their deposition in the form of droplets on the surface area with greater (as compared with d) size. The characteristic radius of the droplets R may be estimated from the condition that the Laplace pressure p should equal the atmospheric pressure, $R = 2\sigma/p$, where σ is the surface tension coefficient. The estimate for titanium yields $R \approx 30$ μm, which agrees well with the visual observations. A similar mechanism of droplet formation is valid for air. However, due to the strong deceleration of droplets in water [1], the distance of their spread is strongly reduced, and the deposition occurs in the close vicinity of the focal spot. After the hole formation, the size of the area occupied with the droplets does not depend on time. This is explained by the fact that when the hole with the diameter of the order of d already exists, no new droplets are produced at further moments of time, and the size of the area is determined by the droplets, deposited at the preceding moments of time only.

3.2. Cutting of plates

Figure 3 presents photographs of the front-side surface of a titanium plate moving in air, illustrating different appearance of the surface after its interaction with radiation, depending on the velocity of the movement. The plate movement direction corresponds to the displacement of the focal spot towards the right-hand edge of the plate. As the velocity decreases, the regime of surface (or through) melting (Fig. 3a) transforms into the regime of periodical (perforated) cutting, when the interaction region is a periodical sequence of holes of nearly the same size (Fig. 3b), and at further lowering of the movement velocity, the perforated cut turns into a continuous one (Fig. 3c). An intermediate regime exists between the perforated and continuous cutting when several holes merge to form a fragment of continuous cut (Fig. 3c). The intermediate regime arises also between the welding and periodical cutting. In this regime the holes with different shapes and sizes are placed irregularly along the direction of movement. An analogous change of regimes is observed at a constant movement velocity and variable radiation power. The instability of cutting, inherent in the transient regimes, is easily reproducible and, probably, has the same nature as the instability in the case of distant cutting of metals, described in [15].

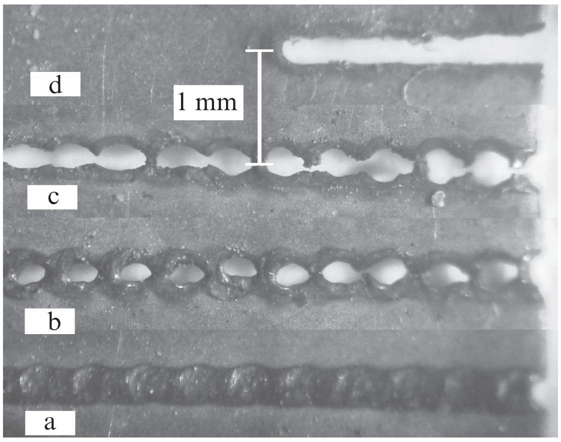

Figure 3. Photographs of the traces on the surface of the titanium plate moving in air at $d = 0.22$ mm, $P = 4$ W, $f = 50$ Hz and $v = 0.2$ (a), 0.14 (b), 0.09 (c), and 0.02 mm s^{-1} (d).

The alternation of processing regimes occurs also under irradiation of moving plates in water (Fig. 4). As in the case of processing in air, one can control not only the width of a continuous cut, but also the parameters of a perforated cut by choosing the velocity of the plate movement or the radiation power. As an example, Table 1 presents the values of the spa-

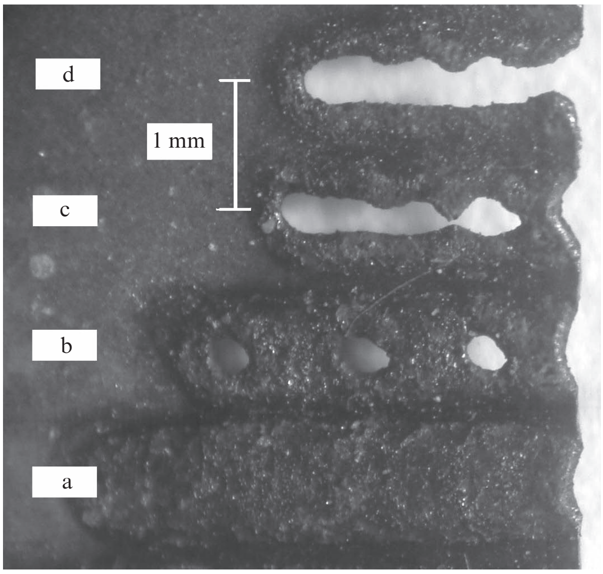

Figure 4. Photographs of traces on the surface of a titanium plate moving in water at $d = 0.3$ mm, $P = 15.6$ W, $f = 50$ Hz, and $v = 0.06$ (a), 0.05 (b), 0.04 (c), and 0.03 mm s^{-1} (d).

Table 1. Spatial period T of holes in a periodic cut vs. v and P in water for titanium at $d = 0.3$ mm and $f = 50$ Hz

T/mm	v/mm s^{-1}	P/W
0.7	0.04	18.6
0.87	0.05	18.6
0.91	0.065	18.6
1	0.03	6.9
0.75	0.02	13.8
0.7	0.04	18.6

tial period T of holes in a perforated cut in water depending on the movement velocity and the radiation power.

The view of the traces is qualitatively different in the cases of irradiation in air and in water. The traces obtained in water are covered with droplets of solidified metal. The width of the traces d_p, as well as the diameter d_d of the area occupied by the droplets in the case of drilling fixed plates, considerably exceeds the focal spot diameter, and becomes smaller at greater velocities (Fig. 5). The reduction of d_p depending on v occurs, probably, because of a decrease in the local temperature of the surface with growing velocity, due to which the lateral pressure of the vapours, pushing the droplets to the periphery, also decreases.

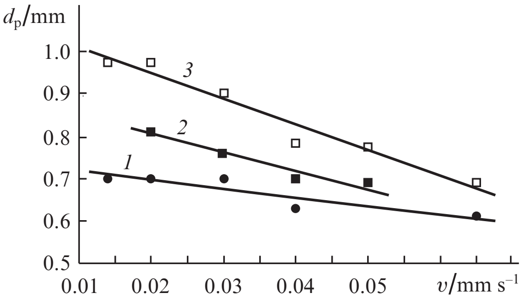

Figure 5. Dependences of the trace width d_p on the velocity v under irradiation of a titanium plate in water [d = 0.3 mm, f = 50 Hz, P = 6.7 (*1*), 13.8 (*2*), and 18.7 W (*3*)].

Let us compare the efficiency of processing the plates in air and in water. The efficiency is of interest both for the continuous cutting regime and for a periodic one, the latter being a representative of dimensional processing of materials with laser radiation. Figure 6 presents the power dependences of the maximal velocity of the target movement in air $v^{\max}$, for which the cut and the stable perforated cut still exist for titanium and stainless steel at f = 50 and 100 Hz. Analogous dependences are presented in Fig. 7 for processing in water at f = 50 Hz. From the dependences presented in Figs 6, 7 it is seen that the maximal values of the velocity at a given power and frequency are smaller for steel than for titanium, and become smaller with an increase in frequency. Same as for the case of plate drilling, these features are qualitatively explained by a different thermal conductivity of the materials and by the change in the pulse energy under the frequency change, the mean power being kept constant. The parameter $\beta = v^{\max}(P/h)^{-1}$, equal to the cut area per unit consumed energy, provides a convenient quantitative criterion of the continuous cutting efficiency [7]. Thus, for titanium at f = 50 Hz the parameter β in air and in water is equal to ~3.8 and ~0.3 mm^2 kJ^{-1}, respectively, and weakly depends on P due to the linear character of the dependences of $v^{\max}$ on P in the ranges of power shown in Figs 6 and 7. As seen from the figures, in water the efficiency of the cutting process decreases, but not so greatly that it could be possible to speak of the efficiency being insufficiently low. For instance, the value $\beta \approx 0.5$ mm^2 kJ^{-1} is typical of the technology of distant cutting of metals in air with the radiation of a cw CO$_2$ laser [7]. It is hard to introduce a quantitative efficiency criterion, analogous to β, for perforated cutting, but for this kind of processing the decrease in the processing velocity in water as compared with that in air has the same order as for the continuous cutting.

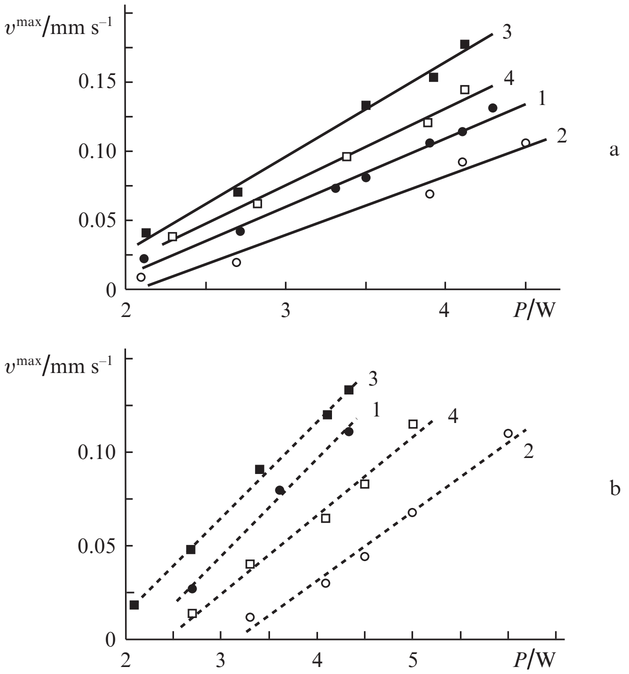

Figure 6. Power dependences of the maximal velocity $v^{\max}$ of stable continuous cut (*1*, *2*) and stable periodic cut (*3*, *4*) in air for titanium (a) and stainless steel (b) at d = 0.22 mm and f = 50 (*1*, *3*) and 100 Hz (*2*, *4*).

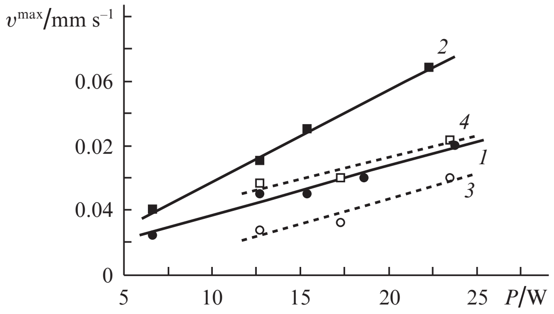

Figure 7. Power dependences of the maximal velocity $v^{\max}$ of stable continuous cut (*1*, *3*) and stable periodic cut (*2*, *4*) in water for titanium (*1*, *2*) and stainless steel (*3*, *4*) at d = 0.3 mm and f = 50 Hz.

4. Conclusions

The studies carried out show that when thermally thin metal plates are irradiated by a repetitively pulse laser in water in the absence of water or gas jets, it is possible to control the regimes of cutting with high enough efficiency. The increase in the time of plate drilling and the decrease in the speed of cutting in water as compared with similar processing in air at the same mean power may be explained by intense heat release in the regime of bubble boiling. When processed in water, the regions of the surface adjacent to the zone of thermal action, covered with droplets of solidified metal, considerably exceed in size the zone of direct thermal action. The deposition of droplets affects the quality of processing and should be taken into account in the case of high-precision processing requirements. The prospects of technologies of laser processing of materials in water and other liquids stimulate setting new problems and developing the research in this direction.

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