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Laser drilling of superdeep micron holes in various materials with a programmable control of laser radiation parameters

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***Abstract*. The possibilities of enhancing the efficiency of laser drilling of micron holes, increasing their depth, and eliminating their conic shape are studied by using a single-mode loop Nd : YAG laser with self-phase conjugation on the gain gratings and passive *Q*-switching by a scanned gradiently coloured F_2^- : LiF crystal. Holes of diameters 15 – 150 μm and depth up to 20 mm with the aspect ratio (ratio of the hole depth to its diameter) of 50 – 155 are drilled in various metals and alloys. It is shown that passive *Q*-switch scanning during drilling provides the increase in the depth and speed of the laser drilling of superdeep holes by a factor of 1.5 – 2.**

Keywords: *laser hole drilling, aspect ratio, programmable control, loop resonator, Q-switching.*

1. Introduction

The laser drilling of submillimetre holes in various materials can successfully compete with mechanical, electroerosion, electrochemical, and electron-beam methods [1]. This method is especially efficient when the aspect ratio k (ratio of the hole depth H to its diameter d) is smaller than 16 because of its high speed, the absence of instrument wearing, and the possibility of drilling deep holes of small diameters and arbitrary spatial shapes at any angle to the surface of a material. The laser perforation of micron holes is of great interest for microelectronics (perforation of printed-circuit boards), aviation industry (airplane outer casing, turbine vanes), and other divisions of machine building (fuel injectors, filters, dies, nozzles, etc.) and also for optoelectronics (fibre couplers in fibreoptic data communication systems) [2, 3].

The maximum aspect ratio (about 250) of holes is achieved upon electric-spark drilling [3]; however, the diameter of holes in this case is a few millimetres. The minimum diameter of a hole obtained by this method is 0.2 mm for the aspect ratio $k < 50$. However, the drilling of deep holes with $d < 0.21$ mm and $k > 16$ involves great difficulties even by using laser radiation [3] because this requires high radiation powers along with a high quality of the laser beam, which makes the laser technology more expensive.

The development of single-mode phase-conjugated Nd : YAG lasers with loop resonators on the gain gratings and passive F_2^- : LiF crystal *Q*-switches [4 – 7] allowed us to increase considerably the efficiency of laser drilling of deep micron holes in samples of fast-cutting steel [6, 7] by using the method of adaptive control of laser parameters based on the scan of a passive laser *Q*-switch (PLQ) with variable initial transmission [8].

In this connection we studied in this paper the possibility not only to increase the efficiency of laser drilling of micron holes but also to increase simultaneously the depth and decrease the conicity of the holes drilled in various materials with the help of a single-mode self-phase-conjugated Nd : YAG laser with a scanned F_2^- : LiF PLQ.

2. Hole drilling method

The experimental setup shown schematically in Fig. 1 includes a single-mode Nd : YAG laser, a beamsplitter, a focusing objective, a target, an IMO-2N pulsed power meter, LFD-2A avalanche photodiodes, and an Agilent 5441A two-beam storage oscilloscope. The target is made in the form of a wedge, which allowed us to change the thickness of a material in which holes were drilled by displacing the sample perpendicular to the laser beam. In this case, the position of the best location plane with respect to the target surface remained invariable.

Holes were drilled in various materials by using a high-

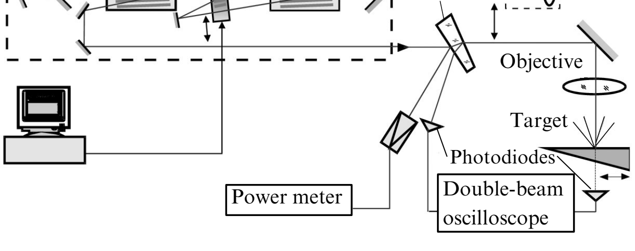

Figure 1. Scheme of the experimental setup.

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power, Q-switched, single-mode, loop, self-phase-conjugated Nd:YAG laser which we developed earlier [4]. The emission parameters of this laser were specially optimised for technological applications [9]. The laser consisted of two K-301B quantrons with active elements of size ∅ 6.3 mm× 100 mm and KDNP-6/90 krypton pump flashlamps. A 13 GDN power supply provided the pump pulse repetition rate in the range from 1 to 30 Hz. The pump pulse duration was 200 μs. Holes were drilled at a pump pulse repetition rate of 20 Hz.

The Nd : YAG laser was passively Q-switched by using a F_2^- : LiF crystal with the variable initial transmission, which could be varied linearly from 20 % to 70 % by displacing the crystal perpendicular to the optical axis. This allowed us to vary continuously the energy and temporal parameters of laser radiation. As the initial transmission of the crystal was reduced, the laser pulse duration shortened and its energy and peak power increased. For the initial PLQ transmission $T_0 = 20\,\%$, the pulse energy W_p in the pulse train achieved 350 mJ and the peak power exceeded 17.5 MW [4]. In this case, three 20-ns pulses with a repetition period of 35 μs were generated in the train. The increase in the pulse energy and peak power is explained by the fact that the increase in the PLQ optical density leads to the increase in the time required to achieve the threshold inversed population and the growth of energy stored in the active element. The PLQ with a high initial transmission has low bleaching losses and a short time required to achieve the threshold inversed population in the active element, which reduces the pulse repetition period in the train and results in the increase in the number of pulses. In this case, although the pulse energy and peak power decrease, the total energy of the pulse train increases, and for the maximum initial PLQ transmission $T_0 = 70\,\%$, the pulse energy of 93 mJ (20 pulses in the train), the pulse duration of ~ 60 ns, and their repetition period of ~ 10 μs, this energy amounts to 1.86 J.

3. Results and discussion

Laser drilling of holes was performed in R18 fast-cutting and 09X18N10T5 heat-resistant steels and their alloys [T15K6 hard alloy (WC-TiC-Co), D16 superduralumin, and AmG6 aluminium alloy].

The laser drilling of superdeep holes (with the aspect ratio ~ 100) can be best performed in the lasing regime obtained by using the part of a gradiently coloured F_2^- : LiF crystal with the initial transmission $T_0 = 50\,\% - 60\,\%$. For these PLQ parameters, the maximum energy of the pulse train is achieved by preserving high enough peak power and pulse energy in the train.

To study the possibility of increasing the depth of micron holes and the efficiency of their drilling, we studied the change in the hole drilling speed for each material at different fixed initial PLQ transmissions. We measured the through-hole-formation time in different parts of the wedge-like target (Fig. 1). Processing was performed by using an objective with the focal distance $F = 100$ mm. Figure 2 presents the dependences of the depth of through holes on the drilling time, which were obtained for a wedge-like R18 fast-cutting steel sample on the setup shown in Fig. 1. Similar dependences were obtained for all materials under study.

One can see that shallow holes ($H < 6$ mm) are most efficiently drilled when the initial transmission of the F_2^- : LiF crystal is maximal ($T_0 = 70\,\%$, curve (*1*) in Fig. 2). In this case, the energy of the laser pulse train is maximal, while absorption losses in the plasma, estimated from the height and emission spectrum of the erosion plume, are minimal, which is explained by a low peak power of radiation. In addition, a high drilling speed demonstrates that the specific energy required for removing a material is low. Indeed, because the pulse repetition rate in the train is high, the mutual influence of pulses on a metal layer being drilled is possible, i.e. a part of the metal melted by a preceding pulse or a train of pulses can be removed from the hole in the form of a melt by subsequent pulses. Therefore, the regime in which the peak power density of a laser pulse is sufficient for a complete removing of the melt is optimal. As the hole depth increases, the radiation power density on the hole bottom decreases due to defocusing, and for $H \geqslant 6$ mm [curve (*1*) in Fig. 2], the drilling speed drastically decreases and the drilling time considerably increases. Thus, for the initial transmission of the F_2^- : LiF crystal $T_0 = 70\,\%$, the maximum depth of the hole is $H_\mathrm{max} = 12$ mm, but only the first 6 mm of the hole depth will be efficiently drilled.

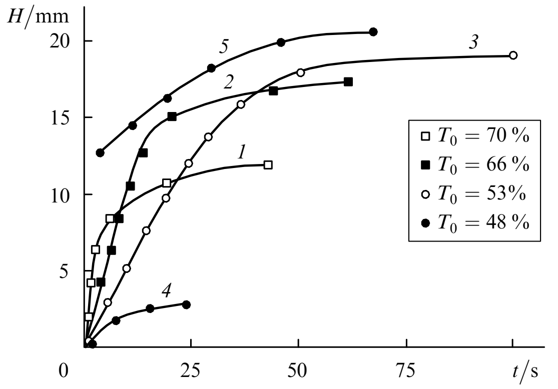

Figure 2. Dependences of the hole depth H in the R18 steel on the drilling time for different initial transmissions T_0 of the F_2^- : LiF crystal.

As the initial PLQ transmission was decreased down to 60 % [curve (*2*) in Fig. 2], the maximum depth of holes increased up to 16 mm; however the drilling speed at the initial stage decreased. To obtain holes with the maximum depth up to 18 mm, the initial PLQ transmission should be reduced down to 53 %. For such transmission of the F_2^- : LiF crystal, the power density maintained over the entire depth of the hole considerably exceeds the threshold value sufficient for removing material in the evaporation regime ($q \approx 10^9$ W cm^{-2}). In this case [curve (*3*) in Fig. 2], the hole drilling speed at the initial stage is considerably lower than that in the regimes with $T_0 = 60\,\% - 70\,\%$. First, this is explained by the fact that, when the optical density of the PLQ is higher, the pulse train energy is noticeably lower for the same pump energy. Second, because the pulse repetition rate in the train is an order of magnitude lower and pulses are shorter by half, the mutual influence of pulses in the drilling region is considerably decreased. As a result, the material is removed due to the evaporation damage mechanism. And finally, the third important factor reducing the drilling efficiency is the screening of radiation by the plasma in the case of a high peak radiation power and intensity. The erosion plume prevents drilling most strongly at the initial drilling stage, when the metal vapour density in the objective focus is maximal. In the process of hole drilling, the metal vapour density in the laser beam waist decreases along with a decrease in the material removal speed (in addition, a part of vapour can condensate on the walls, remaining inside the hole). In this case, the effective ionisation potential of the air – metal vapour mixture increases, while the screening of radiation noticeably decreases. This can explain, in our opinion, the relatively large initial linear region in the dependence of the hole depth on the drilling time.

When the initial PLQ transmission is smaller than 50 %, the radiation screening by the surface plasma increases so that the drilling speed becomes very low [curve (*4*) in Fig. 2]. In this case, the input diameter of the hole increases, i.e. its conicity also increases. However, as a special experiment showed, if the hole depth exceeded 10 mm, then for $T_0 < 50\,\%$ a further drilling of holes with the large maximum depth (over 18 mm) was possible. In this experiment, first at $T_0 = 70\,\%$, a dead-end hole was drilled approximately up to the corresponding maximum depth about 12 mm [curve (*1*) in Fig. 2], which was determined from the drilling time (more than 50 s), and then the coloured F_2^- : LiF crystal was displaced transversely to reduce its initial transmission down to $T_0 = 48\,\%$ and drilling was continued to produce a through hole [curve (*5*) in Fig. 2]. One can see that the limiting depth of the hole increases in this case approximately up to 20 mm.

As the transmission of the F_2^- : LiF crystal was further reduced, the dependence of the hole depth on the drilling time was close to curve (*4*) (Fig. 2) in its initial part. However, the dependence similar to curve (*5*) was not observed when the hole depth was preliminary increased ($H > 12$ mm) in the different drilling regime. This is explained mainly by the refraction and absorption of radiation in the plasma, which was confirmed by the estimate of the fraction of radiation propagated in a through hole of diameter 100 μm in a 5-mm-thick sample. These experiments showed that even a metal evaporated from the walls of the hole was sufficient for maintaining the efficiently screening plasma. In this case, the fraction of radiation incident on the receiving area of a photodiode decreased by more than an order of magnitude.

Based on the results obtained, we increased the hole drilling depth and speed by continuously displacing the PLQ during drilling perpendicular to the optical axis with decreasing the scan speed. In this case, the transmission of the F_2^- : LiF crystal was gradually reduced with increasing the depth of the hole. This provided nearly optimal drilling regime corresponding to the maximum drilling speed at any depths of the hole.

The continuous displacement of the PLQ during laser hole drilling in materials listed above provided the increase in the drilling depth and speed b a factor of 1.5 – 2. Table 1 presents the parameters of laser hole drilling obtained by using two replaceable objectives with the focal distances 50 and 100 mm.

By using an objective with $F = 50$ mm, we drilled superdeep holes of the minimal diameter 15 – 36 μm with the aspect ratio up to 150 in samples of 09X18N10T5 heat-resistant steel, D16 superduralumin, and T15K6 hard alloy. The drilling optimisation by scanning the PLQ and deepening the focal plane to 1.5 mm allowed us to increase the drilling depth of 150-μm holes up to 10 mm in AmG6 aluminium alloy samples, which are difficult to work.

Table 1. Parameters of the laser drilling of through holes.

Material	d/ μm	H/mm	k	C	F/ mm	h/ mm
R18 fast-cutting steel	100	12	120	$< 1:500$	100	0
	120	15	125		100	1
	130	20	155		100	1.5
09X18N10T5 heat-resistant steel	36	3	83	$< 1:500$	50	0
	116	11	95		100	0.5
	150	20	135		100	1.5
AmG6 aluminium alloy	120	5	42	$< 1:200$	50	1
	150	10	67		50	1.5
D16 superduralumin	15	2	133	$< 1:500$	50	0
	25	3	120		50	0
T15K6 hard alloy	15	2	133	$< 1:500$	50	0
	20	3	150		50	0

Note: *d*, *H* and *C* are the hole diameter, depth, and conicity, respectively; $k = H/d$ is the hole aspect ratio; *F* is the focal distance of an objective; *h* is the focal plane deepening.

By using an objective with $F = 100$ mm and PLQ scanning described above, we obtained deepest holes ($H \sim 20$ mm) of diameter 100 – 150 μm in samples of fast-cutting and heat-resistance steel. Figure 3 shows the cross-sectional view of a dead-end hole of depth 12 mm with the 100-μm input diameter drilled in a P18 fast-cutting steel

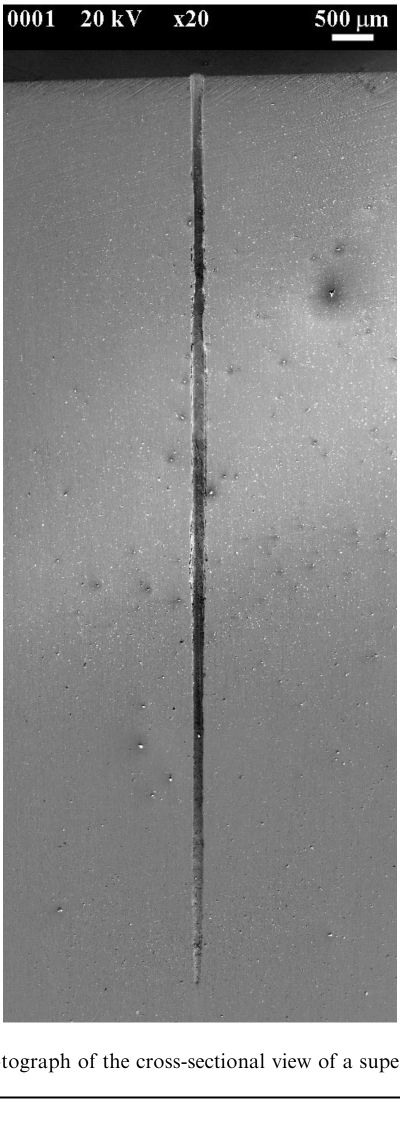

Figure 3. Photograph of the cross-sectional view of a superdeep hole.

sample. The hole was drilled by using the objective with $F =$ 100 mm without focal deepening and moving continuously the PLQ with decreasing scan speed to provide the change in its initial transmission from 70 % to 50 % during the drilling time equal to 1 min. One can see that this drilling method not only provides the increase in the drilling depth and speed but also eliminates the conicity of the dead-end hole over its entire depth, except a narrow (about 10 % of the entire depth) end part. During drilling of through holes in most materials, the conicity of holes is eliminated almost completely ($C < 1:500$) due to the widening of the end of the hole produced by the damage products ejected from the hole.

4. Conclusions

By using a single-mode, loop, self-phase-conjugated Nd : YAG laser passively Q-switched by a scanned phototropic $F_2^- : LiF$ crystal, we have performed highly efficient programmable laser drilling of very deep micron holes with the aspect ratio $k > 100$.

The principle of lasing control by using a PLQ with the transmission variable by displacing a $F_2^- : LiF$ crystal perpendicular to the optical axis, in particular, by using a PC, considerably expands the technological possibilities for applications of high-power single-frequency radiation, considerably increases the depth and efficiency and improves the quality of laser drilling of small-diameter holes.

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