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High-speed ablation of ultradeep channels by a phase-conjugate dynamically controlled passively *Q*-switched Nd : YAG laser

T.T. Basiev, S.V. Garnov, S.M. Klimentov, P.A. Pivovarov,
A.V. Gavrilov, S.N. Smetanin, S.A. Solokhin, A.V. Fedin

Abstract. **Parameters of high-speed ablation of ultradeep channels by controlled pulse trains from a single-mode phase-conjugate dynamic cavity Nd : YAG laser emitting 20 – 200-ns, 70 – 250-mJ pulses at a pulse repetition rate in a train of 40 – 250 kHz are studied. The optimal parameters of ablation are found, for which a long-lived region of a hot rarefied gas was maintained in the ultradeep channel, which suppressed the shielding action of the surface plasma. The control of the lasing process during ablation optimises not only the heating and plasma formation, but also the removal of the processed material in the pause between laser pulses. Adaptive regulation of lasing parameters during ablation made it possible to obtain ultradeep channels of length 8 – 27 mm and diameters 80 – 300 μm of the input and output holes in metals (aluminium, steel and Inconel 718 nickel superalloy) and ultrahard ceramics (Al_2O_3, AlN, SiC).**

Keywords: *ablation, ultradeep channel, surface plasma, multipulse irradiation, controllable Q-switching.*

1. Introduction

High-speed laser drilling of deep channels with a diameter of tens of micrometers is of considerable interest for using in various fields of science and engineering [1, 2]. The geometry of such channels is usually characterised by the aspect ratio, i.e., the ratio of their depth to the diameter. The highest aspect ratios ($\sim$300 – 600) are traditionally obtained during laser processing of polymer materials [2], having bulk absorption and a very low breakdown threshold that does not exceed the threshold of the surface-plasma production, which makes it possible to avoid plasma shielding of laser radiation during drilling. However, the effect of plasma shielding becomes quite perceptible during laser processing (deep drilling) of structural materials (metals, ceramics, etc.), and the losses and channel broadening caused by the shielding due to lateral expansion of plasma reduce the aspect ratio of the obtained channels to 40 [3]. The efficiency of laser ablation and the drilling rate depend strongly on the parameters of the shielding plasma and are reduced considerably, as a rule. For deeper channels, the density and shielding action of the plasma are enhanced further due to restrictions on its expansion [4].

A decrease in plasma shielding was earlier achieved by using femtosecond laser pulses [5] or a combination of pico- and nanosecond laser pulses with a high pulse repetition rate [3]. In the latter case, an increase in the drilling rate and a decrease in shielding can be due to the formation of a long-lived rarefied gas region in the vicinity of the irradiation spot [6]. However, the formation of ultradeep channels with an aspect ratio exceeding 100 and a depth exceeding 2 mm even by using pulse trains requires a high laser pulse energy, which is usually achieved by generating giant nanosecond pulses. To optimise the process and to eliminate shielding, it is necessary to control the operation of a high-power *Q*-switched laser.

It was shown in [7] that a special passive LiF : F_2^- *Q* switch with a variable initial transmission can be used to control continuously the pulse energy, duration and repetition rate of a high-power single-mode Nd : YAG laser with a dynamic loop phase conjugation (PC) resonator over a wide range. Due to self-compensation of intracavity distortions during self-PC, the laser generates high-power pulse trains with a small divergence close to the diffraction limit. The control of lasing parameters by scanning a passive *Q* switch with a variable initial transmission during laser matching permits high-speed drilling of channels of depth more than 10 mm for a hole diameter of about 100 μm in various structural materials [8].

In this study, we analyse the parameters of laser ablation of ultradeep channels in metals, alloys and ceramics produced by controllable multipulse radiation from a self-PC Nd : YAG laser with a dynamic resonator. The analysis was aimed at developing and implementing a new and highly efficient technique of laser perforation of deep and ultradeep (with an aspect ratio exceeding 100) micrometer holes (of diameter 20 – 300 μm) in structural materials, including hard and refractory materials. This laser technology is quite promising for improving the gas-dynamic properties of gas turbines and aircrafts, for production of fuel injectors, prospective ceramic engines, etc.

T.T. Basiev, S.V. Garnov, S.M. Klimentov, P.A. Pivovarov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: basiev@lst.gpi.ru;
A.V. Gavrilov, S.N. Smetanin, S.A. Solokhin, A.V. Fedin V.A. Degtyarev Kovrov State Technological Academy, ul. Mayakovskogo 19, 601910 Kovrov, Vladimir region, Russia; e-mail: ssmetanin@bk.ru

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2. Laser system and processing technique

Channels were drilled in various materials by using a high-power passively Q-switched, single-mode, self-PC, loop Nd : YAG laser with parameters specially optimised for technological applications [9]. Figure 1 shows the optical scheme of a PC laser. The laser emitter consists of two K-301V quantrons with elliptical mirror reflectors, active elements of size $\varnothing 6.3 \times 100$ mm and KDNP-6/90 krypton pump lamps. The pump pulse repetition rate was varied from 1 to 30 Hz with the help of a 13 GDN power supply. The pump pulse duration was 200 μs. Channel were processed by a pump pulse at a repetition rate of 10 Hz.

Passive Q-switching of the Nd : YAG laser was performed by using a $LiF : F_2^-$ crystal with a variable initial transmission that could be changed linearly from 30 % to 76 %. The transmission of the passive Q switch was varied by moving the $LiF : F_2^-$ crystal perpendicular to the optical axis of the laser resonator. This allowed a smooth control over the energy and time parameters of radiation.

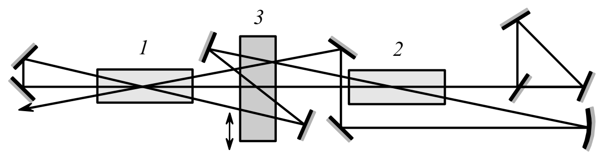

Figure 1. Optical scheme of a laser system for drilling holes: (*1*, *2*) active elements, (*3*) passive Q switch.

Figure 2 shows the dependences of the energy and time parameters of radiation on the initial transmission T_0 of the passive Q switch for the total laser pump pulse energy of 127 J and a pulse repetition rate of 10 Hz. The dependences presented in the figure show that for the initial Q-switch transmission of 30 %, the pulse energy in the train achieves 251 mJ, while the pulse duration and repetition rate in the train are 28 ns and 40 kHz, respectively. An increase in the initial passive Q-switch transmission to 70% leads to an increase in the pulse repetition rate in the train to 100 kHz,

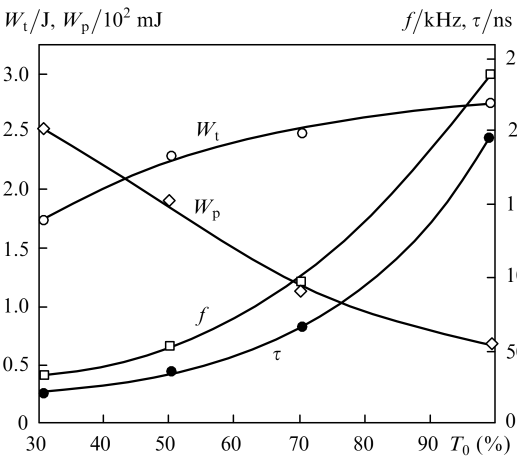

Figure 2. Dependences of the output laser parameters (of the laser pulse train energy W_t, pulse energy W_p in the train, pulse repetition rate f in the train, and pulse duration τ) on the initial transmission T_0 of a passive Q switch.

an increase in the pulse duration to 70 ns, and in the number of pulses in the train from 7 to 18. In this case, the energy of each pulse decreases to 134 mJ, while the total energy of the entire train of pulses increases from 1.76 to 2.42 J. A laser without a passive Q switch, whose parameters correspond to $T_0 = 100$ % (Fig. 2), is also promising for applications. For comparison, Fig. 3 shows two oscillograms of laser pulses emitted by using a passive Q switch with $T_0 = 50$ % and without it. One can see that even without the passive Q switch, a loop self-PC laser generates trains of giant equidistant 200-ns, 40-mJ pulses at a maximum repetition rate of 250 Hz in the self-Q-switching regime of the dynamic resonator, which is produced by periodic recording and erasing of PC mirrors directly in the laser medium [10].

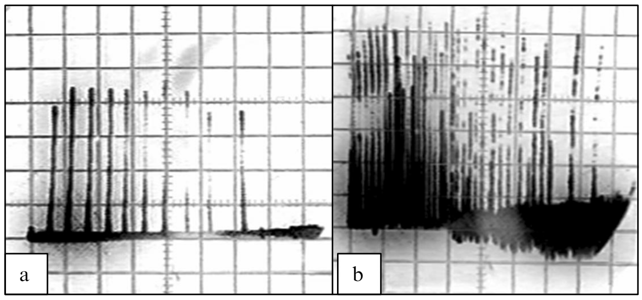

Figure 3. Oscillograms of laser pulses (a) upon passive Q-switching, and (b) self-Q-switching. The sweep is 20 μs per division.

In this study, the main attention was paid to the method of laser drilling of channels [11], in which the energy and peak power of laser pulses were continuously increased during channel formation by displacing the passive Q switch to decrease its initial transmission T_0 in the laser-beam region. The shielding action of the surface plasma decreases in this case because drilling of a channel begins at a low peak power of laser radiation. The energy and peak power of laser pulses during channel formation compensates the decrease in the power density and energy at the channel bottom (which usually occurs with deepening the channel being ablated), and also increases the pressure of the released vapour for removal of the processed material from the bottom of the deep channel, which provides ultradeep drilling. Note that ablation of ultradeep channels with an aspect ratio of ~ 100 for a diameter of ~ 100 μm requires the adjustment of the laser radiation parameters for each material according to a special law as the interaction region penetrates into the bulk of the material for fixed focusing parameters (beam diameter at the focus was 60 μm for an objective with a focal length of 100 mm). We used a pulse repetition rate exceeding 40 kHz to prevent the relaxation of temperature and density of the gas medium in the channel being ablated to their initial values in the period between laser pulses [6], so that their variation would affect significantly the ablation produced by subsequent pulses.

3. Experimental results and discussion

We produced ablation of channels in steel, aluminium and hard refractory materials such as Inconel 718 nickel superalloy and Al_2O_3, AlN, SiC ceramics.

Figure 4 shows for comparison the photographs of sections of high-aspect-ratio channels produced in aluminium and steel samples and a section of an inclined channel in the model of a turbine blade made of an Inconel 718 superalloy under identical conditions of beam focusing to a spot of diameter 60 μm. The photographs are on the same scale. One can see that the channels are needle shaped, which means that this drilling technique provides not only an increase in the channel depth and the processing rate, but also the cylindrical shape of the channel all along its length with the exception of the end part (about 40 % of channel length in aluminium and about 10 % in steel). The channel diameter in steel ($\sim$100 μm in the cylindrical part) was about 1.6 times smaller, and its depth (12 mm) was 1.2 times larger, than in aluminium.

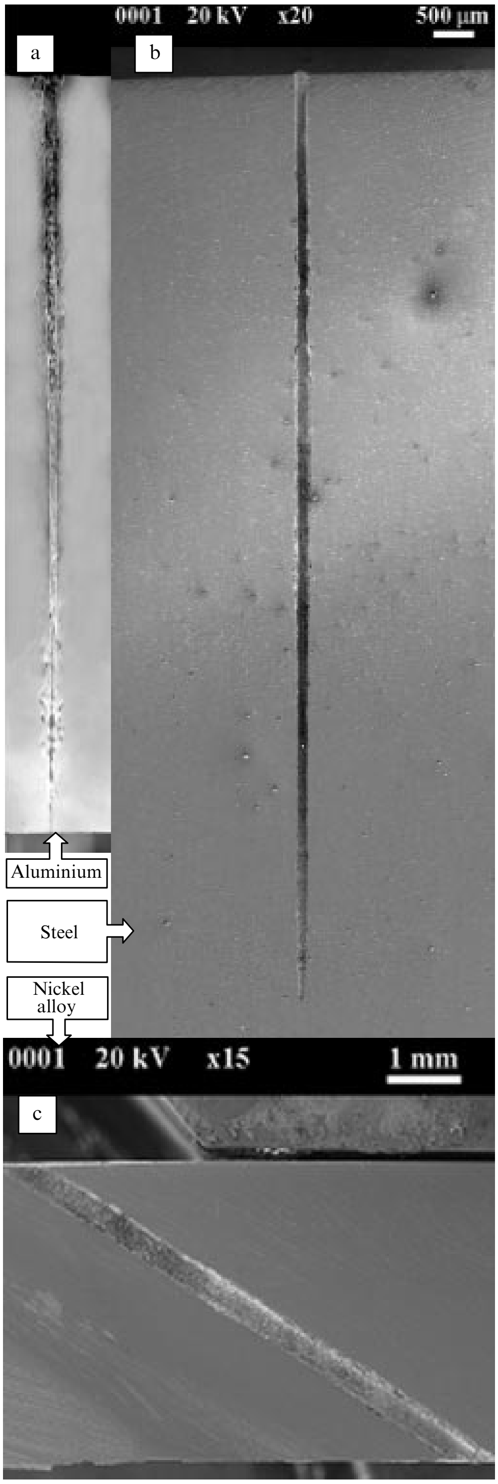

Figure 4. Photographs of channel sections in (a) aluminium, (b) steel and (c) nickel alloy.

The diagram of variation of T_0 during processing of steel samples was optimised in [8]. Drilling in the steel sample was performed by varying the initial transmission of a passive Q switch from 70 % to 50 % with the rate of T_0 variation decreasing linearly to zero over a period of 1 min (which corresponds to 600 laser pulse trains). The time of controlled processing of the steel sample ($\sim$1 min) was six times shorter than the time required for the formation of a through hole in a 10-mm thick aluminium sample. Aluminium is a hard-to-process material with high reflectance, heat capacity and thermal conductivity. The plasma cooling due to heat removal at the aluminium channel walls is an order of magnitude faster than in a steel channel [6] (the thermal diffusivity of aluminium is an order of magnitude higher). The theoretical characteristic pulse repetition rate for aluminium at which the shielding is considerably reduced also increases by an order of magnitude, achieving 40 kHz, i.e. it falls in the working range of pulse repetition rates in the pulse train of the laser. For this reason, multipulse processing by using high-power laser pulses (for $T_0 < 60$ %) resulting in a strong shielding of radiation by plasma, while the optimal diagram of T_0 variation during processing of Al samples was displaced towards higher values of T_0, from 60 % to 76 %.

Through holes in turbine blades must be completely cylindrical. For this purpose, we used an original technique for clearing the channels after completion of controlled drilling of a through hole by 250 pulse trains. We specially initiated a plasma inside the drilled channel by reducing T_0 below 50 %. The decrease in T_0 from 50 % to 30 % caused a backward displacement of the plasma plume localisation region, while the increase in T_0 from 30 % to 50 % caused a forward displacement of the plasma plume in the direction of beam propagation. Such a periodic scanning of the passive Q switch resulted in an increase in the channel diameter at the plasma localisation region, which provided the control of the channel shape. Completely cylindrical channels of diameter 300 μm and depth 7 mm in an Inconel 718 nickel alloy were obtained after clearing for 3 minutes (by 1800 pulse trains) (Fig. 4c). The average rate of formation of such cylindrical channels exceeds 3 μm per pulse train, and more than 50 channels (array of holes in the turbine blade) can be obtained by increasing the pulse repetition rate to 30 Hz.

Then, we performed laser ablation of deep channels in hard refractory ceramic materials Al_2O_3, AlN and SiC. The samples had a size of $8 \times 27 \times 27$ mm. Experiments showed that an optimal mode of passive Q-switching existed for each sample, when drilling occured at the maximum rate. Figure 5 shows the photographs of input and output holes of through channels of depth 8 mm in such samples. In the Al_2O_3 alumina ceramic sample, completely cylindrical (aspect ratio 100) ultradeep channels with input and output holes of diameter 80 μm were obtained in a processing time of about 1 min (Fig. 5a) for an optimal initial transmission $T_0 = 70$ % of the passive Q switch. For the AlN ceramic (Fig. 5b), the processing time was 3.5 times longer for a

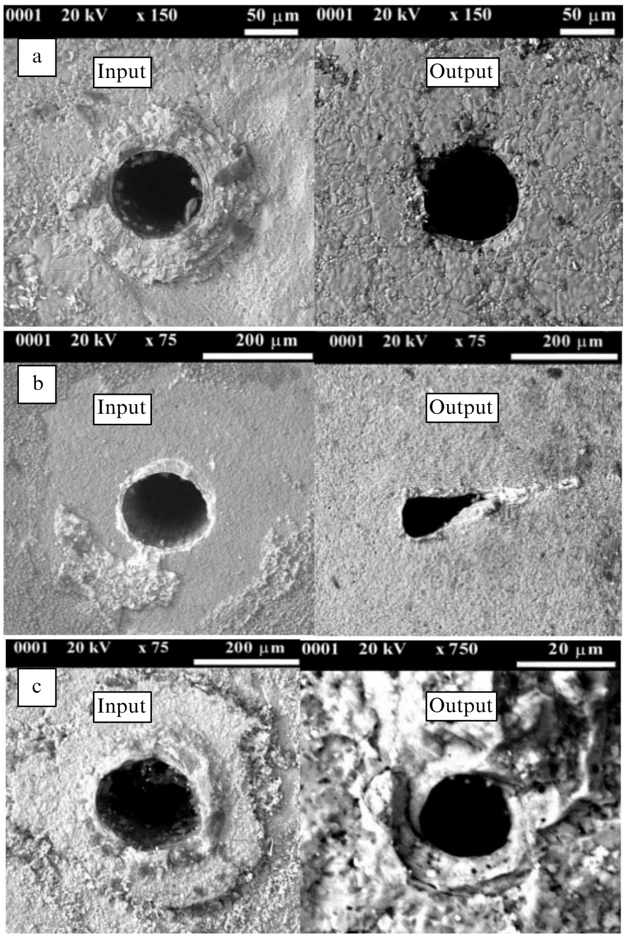

Figure 5. Photographs of input and output holes of channels in (a) Al_2O_3, (b) AlN, and (c) SiC ceramics.

lower optimal value of $T_0 = 65\,\%$. The hole diameter at the channel input was 150 μm, while the output hole was a slit of size 75×150 μm, oriented at right angles to the direction of preferred polarisation of laser radiation. The polarisation dependence of ablation of the material was observed earlier during through drilling of samples of even small thickness (about 1 mm) [3]. The third ceramic material (SiC) investigated by us is the hardest to process. Through holes of depth 8 mm were obtained in it after a prolonged ablation (for about ten minutes) with 'hard' Q-switching by using an optically dense passive Q switch ($T_0 = 50\%$). The channels had the highest conicity: the hole diameter at the channel input was 200 μm, while the diameter at the output was 20 μm (Fig. 5c).

The above results of laser drilling of deep channels in various ceramics show that Al_2O_3 is the most suitable material for obtaining record-depth, small-diameter channels.

We studied for this material the possibility of optimising the processing through adaptive adjustment of lasing parameters to provide efficient drilling of the material. This was possible by visualising drilling processes occurring inside the channel. The matter is that the Al_2O_3 ceramic at a distance of 1 – 2 mm from a channel is transparent for emission of the region heated by laser radiation, and the laser ablation of a deep channel can be visually controlled during experiments.

We have found that the emitting region corresponding to the highest processing temperature and the highest energy release is displaced stepwise along the channel with a frequency of ~ 1 Hz in the optimal ablation regime. This suggests that the material is removed periodically in the channel depth. Adaptive dynamic control of the passive Q-switching of the laser in the T_0 range from 55 % to 70 % made it possible to drill through holes along the longest side of the Al_2O_3 ceramic sample (27 mm). The 27-mm-deep channels obtained in this way had an input hole diameter of 250 μm and a much smaller (by an order of magnitude) output hole diameter. The above method of channel clearance after completion of drilling of through holes provided the increase in the output diameter of a record-deep hole to 80 μm.

4. Conclusions

We have studied the parameters of laser ablation of ultradeep channels in metals, alloys and ceramics irradiated by trains of 20 – 200-ns, 70 – 250-mJ pulses from a single-mode phase-conjugate dynamic cavity Nd : YAG laser at pulse repetition rates of 40 – 250 kHz in the train.

The rate of drilling holes with a large aspect ratio was increased by forming a long-lived (tens of microseconds) region of hot rarefied gas in the channel, which reduces the shielding action of the surface plasma during subsequent irradiation at a high pulse repetition rate.

The method of controlling the laser generation process with a decreasing (from 250 to 40 kHz) pulse repetition rate during ablation optimises not only the heating and plasma formation, but also the removal of the spent material in the pause between laser pulses. This causes an increase in the rate and depth of processing of various materials at micro-processing depths exceeding 7 mm.

An original technique of channel clearance after through drilling by initiating a plasma inside the drilled channel by using controllable 'hard' Q-switching provides a decrease in the conicity of the ablated channels and makes it possible to produce cylindrical channels of depth ~ 10 mm and diameter 80 – 300 μm in various structural materials like steel, aluminium, nickel alloy and ceramics.

The visual monitoring during the adaptive control of the laser parameters in the process of Al_2O_3 ceramic ablation allowed us to obtain record-deep channels of length 27 mm with an input hole diameter of 250 μm.

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