Methods for the solid-state lasers generation modes control for the material laser processing efficiency improving

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Abstract. The areas of modern solid-state lasers application for solving technological problems of materials laser processing are described. The mod composition of laser radiation, which is used in various technological processes of materials laser processing, such as perforation, cutting and welding of materials, and others, are analyzed. The necessity of solid-state lasers functional improvement in terms of increasing the efficiency of their practical use is substantiated. A method for the prospective application of lasers for technological purposes is presented, based on the functional separation of the acting laser pulses of millisecond duration. The results of experimental testing of this method on the basis of a solid-state technological YAG: Nd³⁺ laser are presented. The results of studies of the efficiency of processing materials with different thermophysical properties by laser pulses with a complex temporal shape are presented. The experiments results are analyzed. Potential areas of promising use of this method are noted.

1. Introduction

Today, solid-state lasers represent one of the most promising and dynamically developing areas of modern quantum electronics. At the same time, despite the progress achieved in the development of other types of lasers, solid-state lasers characterize by some advantages and features. For example, proven manufacturing technologies, compactness and stability of operation, good operational characteristics, generated radiation high energy parameters [1-3]. This is a far from complete list of the features of this lasers type, due to which they are well used in laser processing technologies, such as welding, cutting, marking, engraving, heat hardening, alloying, surfacing, and hole drilling [4].

The wide field of application of solid-state lasers determines different requirements for the parameters and characteristics of the generated radiation. In particular, the result and efficiency of laser drilling of deep holes in various materials, including metals, depends on many different factors and parameters [5-7]. These include thermophysical and optical parameters of the material, parameters and characteristics of radiation (wavelength, duration and pulse repetition rate, power density, etc.), parameters of the formation (focusing) of radiation on the surface of the processed material (divergence and diameter of the radiation beam) [8].

The free generation regime of repetitively pulsed radiation (QCW) of solid-state lasers was one of the first regimes used in laser material processing technologies. In this case, the duration of the radiation pulse was varied in the range of ~ 10⁻³ -10⁶ s. However, the peculiarities of the mode, due to the
relatively long pulse duration and, consequently, low pulse power, limits its use in many applications [9].

The next stage in the development of this direction was the implementation and use of the resonator Q-switching mode. Using this kind of mode allows processing materials by pulses with a duration of $10^{-9}$ ns in the evaporation mode without a preliminary process of melt formation. In most cases, the Q-switching mode is realized by using electro-optical and acousto-optical modulators, as well as saturable absorbers [10].

Passive mode locking has opened up new perspectives for precision material processing. In the field of laser micromachining of materials, laser pulses with duration of $10^{-12}$ s minimize heat-affected zones and increase the accuracy and processing productivity [11].

Despite the development of solid-state lasers with short and ultra-short radiation pulses, the use of millisecond and microsecond pulses in technological processes of material processing remains relevant. However, the potential applications of lasers this type have not been fully disclosed [12]. For example, in the case of deep penetration, the effectiveness of laser technology is determined, on the one hand, by the radiation parameters, and on the other, by the optimization of the exposure modes. This is due to the fact that when a hole is formed in the material, a melt accumulates in the penetration channel, which absorbs and defocuses the radiation, which slows down the laser perforation process, can lead to a deterioration in the quality of the hole being formed and to the formation of its taper. Thus, to increase the efficiency of laser materials perforation, it is necessary to increase the rate of removal of the melt from the penetration channel [13].

2. Experimental section

2.1. Theoretical background

Drilling a material with laser pulses with a high repetition rate, the processing pulses influence the metal layer. Part of the material melted by the previous pulse is removed from the formed channel by the subsequent pulse in the form of a melt. Under laser action, the removal of the melt is due to evaporation. However, this process is lengthy and ineffective [5]. The key process that ensures the high-speed removal of the melt from the zone of laser action is the action of the reactive forces of steam recoil. Consequently, the optimal mode is when the power density of the acting pulse is sufficient for an intense increase in the vapor recoil pressure and removal of the melt [14].

In this case, an approach based on the redistribution of the radiation intensity along the time profile of the acting laser pulses turns out to be promising. A single pulse is a combination of long high-energy pulses and short high-power pulses. In this case, the functional separation of the action of the laser pulse is realized. The long high-energy pulse functions to melt the material and form a melt pool. A short high-power pulse effectively removes the melt by intensifying the vapor recoil pressure [14, 15].

2.2. Theoretical background

In [15], the results of experimental studies of the treatment efficiency of structural steel 20 and VT-20 titanium alloy by repetitively pulsed radiation of a technological YAG: Nd$^{3+}$ laser are presented. The laser was based on an emitter based on a plane-parallel cavity 530 mm long. In the optical cavity, two TD2.424.005 laser heads with active elements Y$_3$Al$_5$O$_{12}$: Nd$^{3+}$ (ø 6,3×100 mm) and krypton pump lamps are installed in series. Pulse pumping of the active elements of the first and second laser heads was carried out from two different power supplies. The power supplies were interconnected through a time delay line. The laser radiation parameters are presented in table 1.

| No | Parameter                  | Value  |
|----|----------------------------|--------|
| 1  | Wavelength, µm             | 1,06   |
| 2  | Pulse duration, ms         | ~3     |
| 3  | Repetition rate, Hz        | 10     |

Table 1. The laser radiation parameters
When two pump power supplies worked together, laser pulses with a complex temporal shape were generated. Such a pulse was a combination of a long (~ 3 ms) high-energy pulse and a short (~ 0.5 ms) high-power pulse. In this case, a short second pulse was generated by the laser at the moment of maximum melting of the material caused by the action of the first long pulse. It makes possible to ensure a quick effective removal of the melt pool. Thus, the delay time was ~ 2.5 ms.

The efficiency of material processing was assessed by the time of drilling through holes with laser pulses with usual (Figure 1) and complex temporal shapes (Figure 2). Structurally, the samples of materials were made in the form of plates: thickness - 1 mm, width - 15 mm, length - 70 mm.

3. Results and discussion

The results of the experiment showed that the implementation of a special lasing regime, which provides a complex profile of the temporal distribution of energy in a laser pulse, can significantly reduce the time of drilling through holes in materials. For steel 20 material, the processing time with laser pulses of similar energy decreased from 35 s to 2 s, for titanium alloy from 48 s to 3 s.

4. Conclusions

Thus, the experimental results on drilling materials obtained using the technological YAG: Nd laser demonstrate the broad potential of the generation regime of laser pulses with a complex energy distribution over the temporal shape. The results also show a high technological efficiency of using pulses with a complex temporal shape for the structural materials processing.

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