Research of metallic materials irradiation with high energy pulsed laser impact

A I Blesman\textsuperscript{1,2}, D V Postnikov\textsuperscript{2,3}, G M Seropyan\textsuperscript{4}, E A Tkachenko\textsuperscript{5}, A A Teplouhov\textsuperscript{2} and D A Polonyankin\textsuperscript{2,3}

\textsuperscript{1}Head of the Physics Department, \textit{Physics Department}, Omsk State Technical University (OmSTU), 11 Mira Avenue, Omsk, 644050, Russia

\textsuperscript{2}Associate Professor, \textit{Physics Department}, Omsk State Technical University (OmSTU), 11 Mira Avenue, Omsk, 644050, Russia

\textsuperscript{3}Research scientist, \textit{Scientific-educational center of nanotechnology}, Omsk State Technical University (OmSTU), 11 Mira Avenue, Omsk, 644050, Russia

\textsuperscript{4}Associate Professor, \textit{General Physics Department}, Omsk State University n. a. F.M. Dostoevsky, 55A Mira Avenue, Omsk, 644077, Russia

\textsuperscript{5}Postgraduate, \textit{Physics Department}, Omsk State Technical University (OmSTU), 11 Mira Avenue, Omsk, 644050, Russia

E-mail: nano@omgtu.ru, polonjan@mail.ru

Abstract. In the process of metallic materials treatment by pulsed laser beams with nanosecond duration occurs extremely rapid and intensive heating of their surface. In this case a thin surface layer of material is heated to the boiling point and rapidly evaporates. This leads to arising substantial forces of reactive nature which significantly influence on the shape of the solidified melt and in some cases may cause deformation of the underlying layers. The considered question is relevant in the research of precision treatment of miniature products by laser beams. A metallic powder with microfine material structure was selected as the object of research and was exposed to laser irradiation with nanosecond duration. At the core of reactive forces calculation used the approach similar for laser rocket engines. The paper also presents the model and the results of the forces and the reactive recoil impulse calculation occurring during laser impact to the microfine metallic powder.

1. Introduction

High energy pulsed laser impact is the actual problem in different applications of laser interaction with materials in various areas of science. Some studies are dedicated to the questions of laser pulse spreading inside a bulk of transparent media (sapphire, glass and polymer) [1]. In some works laser ablation of dielectrics [2, 3] and semiconductors [4] is investigated. The physical principles of generation of laser pulses with high power and short duration and their interaction with matter are considered in fundamental works, for example in [5] and [6].
The papers [7] and [8] present the idea of an engine based on thrust caused by the laser evaporation. The important characteristics of the laser engines are: reactive recoil impulse, which is defined as the ratio of magnitude thrust to power of the laser radiation; specific impulse; thrust referred to fuel consumption [9, 10]. The most interesting from the standpoint of energy efficiency are the engines based on a solid materials ablation. In particular there are several possible options:

- direct laser ablation when thrust is generated only by the vapor pressure of the ejected material from the surface [11];
- mixed ablation, when the shock wave is added to pressure of the evaporating material [12];
- laser ablation of structured materials, which include micro and nano powders.

The present paper is devoted to the study of laser interaction with the microfine metallic powder with approach which is similar to laser rocket engines.

2. Research objects and methods

Nickel-based alloy metallic powder with microfine material structure was selected as the object of research. Metallic powder SEM microphotography presented on the figure 1 with different magnification. The elemental composition of the microfine metallic powder will be considered in more detail in next paragraph.

![Metallic powder SEM microphotography](image)

**Figure 1.** Metallic powder SEM microphotography, x100 (a), x1000 (b), x5000 (c) magnification.

For metallic powder irradiation was applied solid state pulsed aluminium-yttrium garnet doped with neodymium ions (Nd: YAG) laser. The basic principles of operation of such lasers can be found in the study [13]. YAG laser with the neodymium rod generates radiation with a wavelength of 532 nm, the pulse duration is 16 ns in free generation mode, the pulse repetition rate is 10 Hz, pulse energy up to 0.5 J, the laser beam diameter up to 6 mm. The appearance of the laser system is shown in figure 2. Laser equipment is located at the area with ISO-5 clean room class.

![Laser equipment](image)

**Figure 2.** The appearance of the Nd: YAG laser systems.

3. The quantitative elemental composition of the microfine metallic powder

The quantitative elemental composition of the microfine metallic powder was obtained with EDS method using a scanning electron microscope JEOL JCM–5700 [14, 15]. The results of analysis are
presented in table 1. As the analysis shows the greatest content of the powder occupy such metals as nickel, cobalt and chromium.

The particle size of the microfine metallic powder ranges from 50 micron and to 60 micron (figure 3). Also was performed EDX analysis of the powder, the results of which are presented in figure 4.

| Element | Mass% | Atom% |
|---------|-------|-------|
| C       | 3.41  | 14.40 |
| Al      | 2.88  | 5.43  |
| Ti      | 1.78  | 1.89  |
| Cr      | 10.67 | 10.42 |
| Co      | 15.84 | 13.65 |
| Ni      | 57.78 | 50.04 |
| Sr      | 3.67  | 2.13  |
| Mo      | 3.89  | 2.06  |
| Total   | 100.00| 100.00|

Figure 3. The metallic powder particle size.  
Figure 4. The metallic powder spectrogram.

4. The reactive recoil impulse calculation

As a result of nanosecond laser irradiation the material dispersion occurs due to intense evaporation with a laser beam from the part of heating. To calculate the reactive recoil impulse using a formula borrowed from [7]:

\[ C_m = \left( \frac{A}{L_{s,hb}} \right)^{\gamma \frac{T_{b,p}}{m}} \frac{1}{\gamma} \]  

(1)

Here \( A \) is the absorption coefficient of laser radiation at the stage of material evaporation, \( L_{s,hb} \) is the specific heat of the boiling, \( \gamma \) is the effective adiabatic index of vaporized substance, \( T_{b,p} \) is the boiling point and \( m \) is the mass of evaporated substance.

Consider ablation at the final stage when the remaining portion of material warmed up to a temperature close to boiling point. In this case, the transition velocity of the phase boundary tends to a constant value determined by the specific heat of the boiling. Using the approaches outlined in [16] it is possible to derive a formula of the intensive evaporation front velocity:
\[ v = \left( \frac{4q_0}{2\rho L_{s.h.b.}} \right)(1 - \frac{L_{s.h.b.}}{cT_{b.p.}})(1 + \frac{I}{1 + (3L_{s.h.b.})(cT_{b.p.})^2}) \]  

(2)

Here \( c \) is the heat capacity, \( \rho \) is the material density, \( q_0 \) is the intensity of the laser radiation, \( r \) is the radius of the laser radiation and \( t \) is the exposure time. Then the reactive recoil impulse for the powder material can be found using the following formula:

\[ C_m = \left( \frac{A}{L_{s.h.b.}} \right) \left( \frac{\gamma T_{b.p.}}{\upsilon \rho \pi r^2 t} \right)^{1/2} \]  

(3)

The impulse shape at energy \( E = 0.19 \) J is presented on the figure 5. The distribution of reactive recoil impulse normalized to the beam power depending on the exposure time for nickel and aluminium is presented on the figure 6.

**Figure 5.** The laser impulse shape at energy \( E = 0.19 \) J.

**Figure 6.** Reactive recoil impulse for nickel and aluminium.

Comparing formulas (1) and (3) it is possible to conclude that the mass of evaporated substance could be estimated according to the formula (4).

\[ m = \upsilon \rho r^2 t \]  

(4)

The dependence of the evaporated substance mass from the intensive evaporation front velocity has a linear character.

### 5. Results and discussion

As a result of pulsed laser exposure of nanosecond duration nickel-based alloy metallic powder is melted, heated to the boiling point and then evaporated (see figure 7a and 7b). On the surface of the powder is formed spherical droplets of different sizes, which were absent before irradiation.

**Figure 7.** Metallic powder SEM microphotography after laser irradiation (a). Formation of droplet phase on the surface of irradiated powder (b). The size of the droplet phase (c).
Most clearly these changes are observed when comparing figures 1c and 7a. The droplet size on the surface of the evaporated substance ranges from 3 to 18 microns (figure 7c) in particle size of the powder distribution from 50 to 60 microns. The elemental composition of the resulting droplets is significantly different from the composition of the initial powder, occurs the elemental redistribution. The greatest change occurs at the oxygen atomic concentration, its composition increases to 34–44% (data from marked droplets, figure 7b) with 14.4% in the initial powder. Also it appears oxygen with a concentration up to 12% in the droplets whereas the initial powder composition doesn’t include it.

6. Conclusion

The developed approach permits to calculate the reactive recoil force and impulse in dependence of the material density and heat capacity, the intensity, the absorption coefficient and the radius of the laser radiation. To important parameters included in the calculation formula are also belong the specific heat of the boiling and the boiling point of evaporated material, the effective adiabatic index of vaporized substance. It is proposed a formula for the evaporated substances mass calculation depending on the intensive evaporation front velocity. Using the developed approach obtained the distribution of reactive recoil impulse normalized to the beam power depending on the exposure time for nickel and aluminium. Reactive recoil impulse decreases inversely proportional to the square root of time with a rise of exposure duration.

The appearance of the droplet phase on the surface of the evaporated substance can be attributed to the substantial results of the study, wherein the droplet size ranges from 3 to 18 microns in particle size of the powder from 50 to 60 microns. Thanks to high-energy laser impact a redistribution of elements in the droplet phase occurs; its composition is significantly different from the initial.

References

[1] Gamaly E G, Juodkazis S, Misawa H, Luther-Davies B, Hallo L, Nicolai P and Tikhonchuk V T 2006 Phys. Rev. B 73 214101
[2] Balling P and Schou J 2013 Rep. Prog. Phys. 76 036502
[3] Stuart B C, Feit M D, Herman S, Rubenchik A M, Shore B W and Perry M D 1996 J. Opt. Soc. Am. B 13 459
[4] Gamaly E G, Rapp L, Roppo V, Juodkazis S and Rode A V 2013 New J. Phys. 15 025018
[5] Luther-Davies B, Gamaly E, Wang Y, Rode A and Tikhonchuk V 1991 Laser Phys. 1 325
[6] Kruer W L 1988 The Physics of Laser Plasma Interactions (New York: Addison-Wesley)
[7] Rezunkov Yu A 2011 Izvestiya vysshikh uchebnykh zavedeniy. Priborostroenie 54 7
[8] Rezunkov Yu A 2007 Opt. Zh. 74 20
[9] Ignat’ev A B 2008 Integration of high-power laser sources with the means of formation, orientation and precise beam pointing (Moscow: Mirea)
[10] Ageev V P, Barchukov A I, Bunkin F V, Konov V I, Prokhorov A M, Silenok A S and Chapliev N I 1977 Sov. J. Quantum Electron. 7 1430
[11] Pakhomov A V, Thompson M S and Don A G 2003 Ablative laser propulsion: a study of specific impulse, thrust and efficiency Beamed energy propulsion: First International Symposium on Beamed Energy Propulsion (Huntsville, Alabama, USA, 5–7 November 2002) (AIP Conf. Proc. vol 664) ed. A V Pakhomov pp 194–205
[12] Phipps C R, Seibert D B, Rouse R W, King G, Campbell J W 2000 Very high coupling coefficient at low laser fluence with a structured target High-Power Laser Ablation III (Santa Fe, NM, USA, 24 April 2000) (Proc. SPIE. vol 4065) ed. Phipps C R pp 931–938
[13] Fibrich M, Hamblálek T, Němec M, Šule J and Jelinková H 2014 Laser Phys. 24 035803
[14] Blesman A I, Postnikov D V and Polonyankin D A 2015 IOP Conf. Ser.: Mater. Sci. Eng. 81 012031
[15] Blesman A I, Postnikov D V and Polonyankin D A 2015 Procedia Eng. 113 413
[16] Rykalin N N, Uglov A A, Zuev I V and Kokora A N 1985 Laser and electron beam processing of materials (Moscow: Mashinostroenie)