Mass transfer in ablation process with large angle of laser ray incidence on target and small distance between target and substrate

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Abstract. This paper presents the results of research of laser ablation, carried out at 85° incidence angle of the laser ray to the normal to surface of target with simultaneous spatial restriction of plasma torch. It is shown that laser radiation reflected from the target falls on the substrate and produces ablation. Consequently ablated material of the substrate is transferred to the target. It is found, that direct and reflected from the target laser radiation form periodic wave-shaped structures on the surface of target and substrate.

1. Introduction
Wide range of possibilities of the method of pulsed laser deposition (PLD) makes it a subject of a growing interest in the industry [1]. One of the unique features is the ability of laser radiation to generate plasma at a considerable distance from the laser and in the inner cavities of various products [2], that in the end allows to modify internal surfaces of cavities, including coating by PLD method. Characteristics and technological capabilities of spatially bounded plasma formed by laser radiation in the quasi-closed volume of hollow bodies now is not fully understood, despite the theoretical and experimental studies held by different groups of scientists [3]. With spatial restrictions significantly increases the concentration of excited particles in the laser plasma, what proved very useful in laser-induced breakdown spectroscopy [4], and also changes the shape of the plasma torch. When plasma torch is directed forward (obvious characteristic of the laser-induced plasma) its parameters and shape substantially depend on target-substrate distance. When the distance is small the interaction of the substrate and plasma torch should significantly affect morphology of the film deposited on the surface.

Most researches of laser ablation and PLD were carried out at \( \theta = 45° \) incidence angle of the laser ray to the normal to surface of the target. There are still few researches at \( \theta \geq 80° \), although they are of considerable interest for a variety of practical applications: analysis of the chemical composition of the target material [5], development of efficient soft X-ray lasers and plasma accelerators [6], micromachining [7], medicine [8], etc. Ablation with \( \theta \geq 80° \) and spatial restriction of plasma during film deposition process was used in [9]. However, the experiments were carried out at atmospheric pressure using the method of air blowing for removing particulates from the film deposition zone, which is unacceptable for the deposition on the internal surfaces of cavities. Previously, during experiments with film deposition by PLD method with small target-substrate distance we have found...
re-evaporation of the film by laser radiation reflected from the target [10]. The experiments were performed in studies on the coating of internal surfaces of pipes at angles of incidence of laser radiation at the target 20°, 30° and 60° to the normal to the target surface. In this paper ablation was performed at 85° angle of incidence to the normal to surface of target, i.e. close to sliding angle, with simultaneous spatial restriction of plasma torch. Results of this research are interesting in the aspect of studying of modification of inner surfaces of hollow bodies.

2. Experimental
Experiments were conducted on laser stand [2]. Ablation was made by YAG:Nd laser LTI-215(M) with pulsed pumping and modulated quality factor. Parameters of laser radiation: wave length $\lambda = 1064$ nm with maximum pulse energy $I = 180$ mJ; pulse length $\tau = 10$ ns; pulse frequency $f = 30$ Hz; beam divergence $\gamma = 5$ mrad. Laser radiation was focused on the target by a lens with focal length $F = 100$ mm. The size of laser mark on the target was 1 mm, therefore the power density of laser radiation on the target was $W = 2.2 \cdot 10^9$ W/cm$^2$. A more detailed description of the installation can be found in [11]. With an incidence angle 85° to the normal, the laser mark on the target takes the form of an extremely elongated ellipse 7 mm in length, so its area increases 6 times in comparison to one formed at the normal incidence, and the power density of laser radiation on the target is correspondingly reduced to $3 \cdot 10^8$ W/cm$^2$. A diagram of the experiment is shown in figure 1. Plates with 1 mm thickness were used for both the target and substrate. Material of the target: alloy Ti ($\sim$Al = 7 %, $\sim$Si = 0.5 %), and substrate material is polished steel SUS 304 of industrial supply. Number of pulses – 150.

Target was set at 3 mm distance from the center of laser beam mark, thus providing significant plasma torch restriction. Target and substrate surfaces were chemically cleaned and then placed in the working chamber, which was vacuumed to pressure $P = 10^{-3}$ Pa. Ablation was conducted at pressures $10^{-3}$ and 50 Pa, under Ar presence. Morphology of surface and chemical analysis of specimens were studied by means of optical microscopy on microscope “Carl Zeiss Jena” INTERFACO A E and scanning electron microscope FEI Quanta 600FEG with microanalysis system EDAX Trident XM4.

3. Results and discussion
As a result of ablation material of the target transferring to the substrate (figure 2), the spot of the coating is formed in an almost-round shape, in spite of the elliptical shape of the laser radiation spot on the target. This happens because of incomplete «flip-over effect», which is theoretically described in [12]. This effect results in a 90° rotation of the ellipse on the substrate relative to the ellipse on the
target, due to the higher pressure of torch vapors dissipating in a radial direction, relative to the direction to the surface of the target. In this case, extremely small distance between target and substrate does not allow the «flip-over» process to fully complete. Microanalysis of elements in the center of the film deposition zone found an increase in Ti up to 6.21 % in comparison to its content in steel substrate 0.4 % after ablation by 150 pulses under high vacuum. This confirms efficiency of ablations at a high angle of incidence of the laser ray to the target. At the same time during the ablation by 10 pulses, the content of Ti is significantly lower. In our opinion this is due not only to the difference in the total duration of radiation in both modes, but also to the stronger development of relief of the target surface under 150 pulses, which increases the efficiency of ablation.

**Figure 3.** Laser mark on the Ti target (150 pulses, \(P = 10^{-3}\) Pa).

**Figure 4.** Laser mark on the Ti target (10 pulses, \(P = 10^{-3}\) Pa).

Photographs of the centre of the laser radiation mark on the surface of Ti target after 150 and 10 laser pulses and pressure \(P = 10^{-3}\) Pa are shown in figures 3 and 4. Both pictures show structures of periodic waves. Short elements of wave formed at 10 pulses, and then grow together in long waves at 150 pulses. Thus, the period of the wave stays the same. At 50 Pa pressure periodic structures still exist, but their length stays short at 150 and 10 laser pulses. Periodic wave structure-forming-processes are initiated by laser irradiation of surfaces of semiconductors, metals, polymers, dielectrics and fluids at different parameters of laser ray and are detailed in different literature sources.

At oblique fall of laser ray at large angle to the normal to the surface, strong reflection of radiation from the surface is going on along with ablation. Reflected ray at small target-substrate distance falls to the substrate and ablates its surface. Ablated material transfers to the surface of the target, i. e. on this stage of the process target becomes substrate. Reflected from the target ray makes mark on the processing surface also in the shape of strongly elongates ellipse with the same length approximately 7 mm (figure 2).

Photo of the surface of substrate in the center of the reflected laser radiation impact zone is given in the figure 5. Highly developed wavy surface is shown, and that says about surface melting under irradiation and accordingly about significant value of reflected radiation. Thus, influence picture of reflected radiation on the substrate surface is similar to the influence picture of direct laser radiation on the target with only difference in length of the wave elements, which in this case are shorter.

Figure 6 presents the photo of zone of film deposition spot on the target, produced by the ablation of substrate by reflected ray. We see cracks formed on the film. Spectra of the target and of this film are shown in figures 7 and 8. It is seen that significant transfer of material from substrate to target has occurred.
4. Conclusions
Research of laser ablation of Ti alloy at laser radiation angle of incidence on the target 85° from the normal to the surface with simultaneous spatial restriction of plasma torch are carried out. It is shown, that in the result of significant reflection of laser radiation from the target part of it falls on the substrate and produces ablation. Ablated material of the substrate transfers to the target. It is determined that direct and reflected from the target laser radiation forms periodic structures of waves on the surface of target and substrate consequently.

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