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Theoretical and Experimental Comparison of Splashing in Different Materials

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Abstract

This paper presents the comparative results of experimental and theoretical calculations for splashing in PLD (Pulsed Laser Deposition) experiments. A 10mJ Q-Switched Nd:YAG (1.064 μm, 1.1 MW) laser was used for deposition Experimental results were comparable with theoretical prediction about Splashing. Splashing was observed only in the case of copper but not in the case of graphite both experimentally and theoretically, which was due to the greater skin depth of graphite than copper.

Introduction

In material science, lasers play a significant role in various applications such as localized melting during optical fiber pulling, laser induced rapid quench to improve surface hardening, and most recently, Pulsed Laser Deposition (PLD) for growing thin films [1].

Laser radiations provide the thermal energy to the target that melts it, during this process micro-sized particles ejected from the surface of the target, which is named as the Splashing. The phenomenon of splashing was demonstrated in the first Pulsed Laser Deposition experiment and has been frequently discussed ever since [2].

Surface boiling was referred as true splashing [3]. It occurs if the time required transferring the laser energy into heat energy is shorter than that of required evaporating a subsurface layer of thickness of the order of skin depth. The recoil pressure of shock wave of the plasma plume produces splashing forming the long needle shaped microstructure [2]. These micro-sized structures point toward the incoming laser radiations due to the shadow effect [4]. Mechanically, these can be broken very easily by thermal shock induced by the intense laser radiations. The process is termed as exfoliation [5].

Splashing can be reduced by reducing the laser power density and also by use of mechanical particle filter, which is also called velocity selector. Velocity selector is a multiple-fin rotor operated at 3000 rmp placed in the evaporants path to prevent particles with a velocity less than 1000 cm/s from reaching the substrate surface.

Experimental setup

A copper target and a glass substrate were placed in vacuum chamber, at a pressure of 10^{-3} torr. A 10mJ Q- Switched Nd:YAG (1.064 μ) laser was used to ablate the copper and graphite targets. Substrate was placed at a distance of 0.5 cm from the target, at room temperature. Laser radiations focused at the surface of the target at an angle of 45° with the normal of the target and substrate was paced along the normal of the target as shown in the figure [1]. To attain the uniformity, substrate was rotated with a simple regular dc motor and a computer controlled stepper motor was used to remove the problem of plasma plume orientation due to formation of crater that can disturb the uniformity of thin films. After the completion of 5000 laser pulses, copper target was replaced by a graphite target and glass substrate was replaced by a silicon substrate at the same parameters.

This time 2000 laser pulses were irradiated at the graphite target. Thin films were studied by a metallurgical microscope. High density and smooth surfaces are the desirable features of a target material in order to minimize splashing [2]. To conform the splashing copper target was irradiated in air for 200 laser pulses.

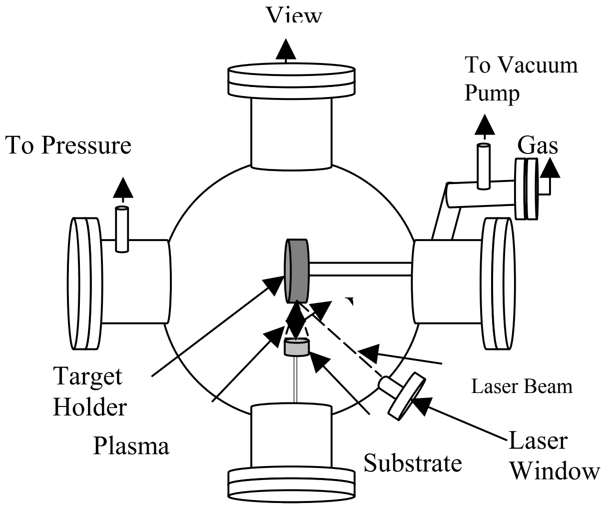

Fig. 1: Schematic of the experimental

Results and discussion

When the laser radiations hit the target, it penetrates in to the target material with out any conversion of electromagnetic energy into any other type of energy, this penetration region is called optical region or skin depth. The relation can calculate skin depth,

$$L_o = \frac{252}{\sigma f k_m}$$

Where,

σ = Electrical conductivity of the target material.

f = Frequency of the laser radiations.

k_m = permeability of target material.

Above relation shows that laser penetration depth increases by decreasing the laser frequency or by using a target of low electrical conductivity. Skin depth can also be calculated by taking inverse of absorption coefficient of target material $\alpha^{-1} \propto L_o$. The absorption coefficient of graphite is 5×10^5 cm^{-1}, thus skin depth for graphite is 20 nm. As laser radiations provide the thermal energy to the target, so a thermal region is produced where electromagnetic energy converts into the thermal energy. The thermal region depth can be calculated by the following formula,

$$L_{th} = 2\sqrt{D_{th}\tau_p}$$

Where,

τ_p is the laser pulsed duration and D_{th} is the thermal diffusivity.

Thermal diffusivity is dependent on target material properties, which is given by,

$$D_{th} = \frac{K}{\rho c}$$

K = thermal conductivity of the target material.

ρ = mass density of material.

C = heat capacity.

L_{th} is that part of the target that gains thermal energy during the laser mater interaction and skin depth is ablated. For metals skin depth is of the order of the "nm" but thermal region is of the order of the "µm". Which of the parameter (L_o or L_{th}) will be greater, that will be considered only. For example, if L_o is greater than L_{th}, then there will be only optical region in the target material. Based on Ready's model, Schwarz and Tourtellote [6] estimated the maximum laser power density that a solid surface can absorb without causing splashing to be,

$$D_{\max} = \frac{L_o \rho H_{ev}}{t_r}$$

Where,

L_o = skin depth

ρ = Mass density of the target material

H_{ev} = heat of evaporation

t_r = relaxation time of the hot electrons in the target surface layer, which is abate 1% of the reciprocal of an equivalent Debye oscillator, which is generally of the order of 10^{-14} to 10^{-15}sec.

It is clear from the calculated values that the required threshold splashing energy for graphite is tow times the intensity of the laser (6.1×10^{12} W/cm^2) radiations, so used laser could not produced any splashing on graphite target as shown in the figure (3) of a uniform thin film of graphite.
While in the case of copper laser intensity is five times great than the required threshold splashing intensity, so intensity of Nd: YAG laser was sufficient to produce shaping on the surface of the copper target.

Figure 3: photograph of uniform thin film of graphite

Tow types of Splashing are clearly seen from the SEM (Scanning Electron Microscope) photographs (figure 4) of the irradiated copper target. Among them Surface Boiling or True Splashing is the most dominant in which surface of the target material is boiled owing to thermal energy of the irradiated laser. Second prominent phenomenon is Exfoliational Splashing, which causes flakes detachment from the target owing to repeated thermal shocks.

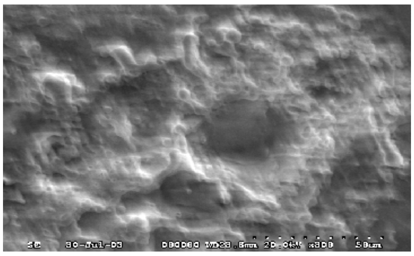

Figure 4: SEM Micrograph (×800) of laser irradiated copper target, which shows the Surface Boiling and Exfoliational Splashing.

Conclusions

It was concluded that splashing was not occurred in graphite but produced in copper target. Thus theatrical calculations completely agreed with experimental evidences. Therefore theatrical models should be calculated for deposition of uniform thin films.

References

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