Influence of target structure on laser plasma generation efficiency

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Abstract. Spatial restrictions on heat transfer imposed in foil and sintered powder titanium targets have resulted in sufficient increase of efficiency of laser plasma generation as compared to bulk Ti targets. Especially at low laser fluences, where target material input in plasma is higher than ambient air’s. Also, the pattern of momentum coupling coefficient $C_m$ dependency on laser fluence $F$ has changed from convex to concave. Minimum difference in $C_m$ values for bulk and foil targets was 1.68 times, maximum – 1.5 orders of magnitude (always higher for foil). At the impact on sintered porous targets momentum coupling coefficient was lower than for foil, but normalised by mass density, the results were about equal. To our mind, obtained results show that suppression of heat dissipation in porous targets can be same efficient as in foils, but with more benefits for feeding systems and energy efficiency of laser plasma generators.

1. Introduction
Heat transfer in laser irradiated materials defines the amount of energy left for plasma production. The amount of residual energy, i.e. staying in target, normalized to the incident one reaches 0.6 or even more [1]. The difference in laser ablation processes of well (metals) and poorly (polymers) heat conducting materials is well known. The usual parameters for laser ablation efficiency evaluation are specific ablation rate $\Delta m/E$, momentum coupling coefficient $C_m$, specific impulse $I_p$, and energy efficiency $\eta$ [2]. The values depend a lot on laser radiation parameters and ambient conditions [3].

To reduce heat losses in metal targets, foils [4, 5] and thin films [6, 7] are often used. However, for plasma generation facilities, foils and films are not always available due to possibility of wrapping or burning through at high laser intensities. Despite even higher ability to reduce heat losses due to lateral transfer also confined, data on laser ablation of porous metals are nearly missing. Although, porous silicon is investigated for electrical micro-thrusters [8, 9]. Laser plasma generators could benefit from using porous targets sintered from powders due to easier powder storage and transfer systems [10], ability for active layer regeneration. This technology is now well developed in 3D-printing [11].

Moreover, porous media provide good abilities for making tailored targets (in a larger scale than multilayered thin films), consisting of different phase materials (impregnated with liquids, gas filled). Better impact localization because of mass transfer restrictions could also be beneficial. Great surface area could be used for laser induced chemical reactions. It is surprising that laser ablation of this class of materials is so under investigated (despite the former is used for the manufacturing of the latter for a long time [12]). By the moment only the applied research in this area could be found in laser cleaning [13].
Polymer powder ablation was studied in [14], but the results were not so good since piling the powder up led to high losses because of splashing (similar to liquids [15]). Compacted (compressed up to 40 MPa) powder ablation led to high mass consumption, perhaps, due to still weak links between grains easily broken by blast wave. The attempt to introduce metallic powder in a polymer matrix also did not give the expected result since grains left the matrix before full evaporation [16]. We suggested that sintered powders should have strong enough links between grains to behave as a bulk material, but with low heat conduction. So the aim of our study was to check if this is going to be true and to compare the results in terms of momentum coupling coefficient with bulk and foil Ti targets.

2. Experimental layout

The sketch of experimental setup is presented at Figure 1. We irradiated targets at ambient conditions in a single pulse mode using frequency doubled Nd:YAG laser (532 nm, 12 ns, up to 80 mJ, Lotis TII LS-2147), spot diameter at target was 224 μm. Incident laser energy was measured by control photodiode calibrated following standard procedure, using energy meter (Ophir 30A-P-RP) placed just after lens instead of a target. Recoil momentum has been measured using a calibrated force sensor (531 mV/N, PCB Piezotronics 209C11). Electric signals were recorded using PC-coupled digital oscilloscope (Aktakom ADS-3114). Force signal was integrated by time to get recoil momentum.

The targets were: 1.5 mm thick Ti sheet (considered as bulk); 0.1 mm thick Ti foil; 0.9 mm thick porous target made of sintered titanium powder (fine gas filter manufactured by VMZ-Techno, 0.26 porosity = non-solid volume / total volume, average pore dia. 8 μm). To avoid targets jumping, those were attached to the sensor by sticky tape. Ablation mass consumption has been measured for 100 pulses (in a scanning mode 0.2 mm/s and 10 Hz pulse repetition) using analytic scales with 10 μg precision (CAS CAUW-120D).

3. Results and discussion

Data on momentum coupling at laser ablation of titanium are very poor and are unavailable for direct comparison. Most of those are referenced in [17]. The results of our measurements are presented at Figure 2. For the targets with heat transfer restrictions (2, 3) the dependency has quite different pattern as compared to the bulk titanium. Minimum difference in $C_m$ values for bulk and foil targets was 1.68 times at high fluences, maximum – 1.5 orders of magnitude (at lower fluences, always higher for foil).

At the impact on sintered porous targets, momentum coupling coefficient was lower than for foil ($C_m(F)$ dependency pattern was identical), but normalized by mass density, the results become about equal. For foil and porous targets, momentum coupling (both values and dependency pattern) at low fluences was higher than that for bulk.

![Figure 1. Experimental setup (a) and typical force signal (b):](#)

1 – target, 2 – force sensor, 3 – lens, 4 – control photodiode, 5 – laser, 6 – digital oscilloscope
fluences was similar to polymers (which are heat insulators) [18] and metals at femtosecond laser irradiation (when heat affected zone is very small) [19]. Similarity of values obtained for all targets at high intensities can be explained by reduction of residual energy coefficient decreases at laser fluence increase [1] and by increase of ambient air input in recoil momentum, making target properties not so important.

The results presented at Figure 2a are well fitted with a curve \( \ln(F/F_a)/F \) [20] corresponding to ablation threshold of \( F_a = 1 \text{ J/cm}^2 \). Those correspond well to the results of [21]. Estimating \( I_{sp} \) and \( \eta \) from this results makes it obvious, that at high fluences input of ambient air in recoil momentum becomes dominating since most of laser energy is absorbed before target surface. So ablation exhaust velocity calculation as \( <v> = C_m/(\Delta m/E) \) is not correct since weight of air involved in thrust generation is sufficient, same as in gas turbine jet engine. Absolute mass removal was nearly asymptotic at fluences greater than 120 J/cm\(^2\), so it looks like some certain amount of target material needs to be ablated for near-surface area saturation. Ablation rates at maximum fluences of 250 J/cm\(^2\) were 4.0 μg/J for bulk target, 2.0 μg/J for foil and 3.1 μg/J for porous. As expected, ablation threshold decreases at heat transfer restriction, and air influence becomes pronounced at lower fluences. This leads to great energy efficiency increase with calculated values far over unity same to shown for laser-induced shockwaves in [22], so target structure becomes not so important fluences higher than ca. 100 J/cm\(^2\). This finding is important for laser shock processing [23] since allows to reduce laser power. Porous layer could be easily coated on almost any surface, and then removed if needed.

![Figure 2](image.png)

**Figure 2.** Specific ablation rate (a) and momentum coupling coefficient (b) at impact on Ti targets:

1 – bulk (1.5 mm), 2 – foil (0.1 mm), 3 – porous

Neither target microscope imaging, nor weighing revealed increased mass consumption from a porous media, so our initial suggestion about sufficient strength of inter-grain links was correct. Another influencing parameter is focal spot to grain size ratio. In our case it was \( \sim 11 \), so even at comparatively weak links there should be no large scale destruction. Focal spot is unknown for [14], but grain sizes were 40 μm and 300 μm, so the discussed ratio should have been significantly less. It is still unclear how ablated mass measurement could be affected by oxidizing – ca. 1.7 mm width sky blue stripes (color is characteristic for titanium oxide) left along scans at all targets. Further experiments in vacuum could answer questions regarding to ambient air influence.
4. Conclusions

Spatial restrictions on heat transfer imposed in foil and sintered powder titanium targets have resulted not only in sufficient efficiency of gas-plasma flows generation increase as compared to bulk Ti targets (especially at low laser fluences), but also in change of the pattern of momentum coupling coefficient $C_m$ dependency on laser fluence $F$ from convex to concave.

To our mind, this confirms the role of heat dissipation processes in decrease of efficiency at the impact on bulk targets. In case of impossible use of foil targets, thick porous targets could be used nearly same effectively. Porous media and powder based working media seem to be rather promising for laser plasma generators.

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