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On the relationship between the dynamics of the power density and workpiece surface texture in pulsed laser ablation

Ming Chu Kong [a], Calin B. Miron [a,b], Dragos A. Axinte (2) [a,*], Samantha Davies [c], James Kell [c]

[a] Division of Manufacturing Engineering, School of Engineering, University of Nottingham, UK
[b] Division of Applied Mathematics, School of Mathematical Sciences, University of Nottingham, UK
[c] Rolls-Royce, Derby, UK

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ABSTRACT

The use of pulsed laser ablation to generate controlled 3D micro features in various materials needs to control the effect of superposition of individual laser footprints upon surface geometry. Starting from the actual footprint of a single laser shot, the paper presents a model that enables the prediction of surface texture in pulsed laser ablation; the model is simple, yet effective by considering dynamics process parameters (pulse duration, frequency, scanning speed), allows the use of different beam energy distributions while being independent on the target material. Validation trials performed in Ti6Al4V showed a maximum error in predicting surface texture of 9%.

1. Introduction

With higher demand for ever-more sophisticated micro features generated in a variety of materials, pulsed laser ablation (PLA) has become a key technology for high value-added industries.

The availability of high pulse energies, facilitated by small spot diameters (<50 μm) and (ultra)short pulse durations (μs–ps) [1], made possible fine material removal on a wide range of target materials (e.g. Ni/Ti alloys, glasses, hard composites). This technology resides in the ablation fluence (threshold 0.2–20 J cm^{-2}) 2) that changes the material state directly from solid to vapours in very short time while little metallurgical surface damage [2]. PLA can be used for the generation of complex micro-features [3] by employing beam path strategies [4] 'borrowed' from machining. In this respect, packages for the generation of beam path for PLA to produce complex geometry surfaces are not fully developed. This is mainly due to the lack of modelling of beam footprint in its dynamic development along a predefined path. Indeed, some models on material removal mechanism on PLA have been explored; they are related to single pulsed spot [5] or depth [6]/width [7] of the machined trench for a moving pulsed spot or prediction of material removal rates [4]. Multi-physics modelling of laser ablation to determine the influence of pulse length and energy on the resulting microstructure [8] or the mechanism of ejected material [9] has been reported. However, all these approaches either are computationally demanding and/or require simplifying assumptions; hence, they are difficult to be utilised to predict the surface texture in real processing environments. Therefore, it would be beneficial if a generic model can be developed for simulating the resultant surface obtained as a superimposition of individual footprints of PLA; this could open avenues for developing CAM packages for PLA to enable controlled generation of freeforms.

* Corresponding author.

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The paper proposes a novel approach for modelling the texture obtained during PLA by taking into consideration its dynamic parameters (e.g. pulse duration, frequency and beam feed speed). The method relies in capturing the 'response' of the material to a particular set of energetic parameters of the beam (resulting in a known fluence) by initially modelling the shape of a single shot on the target surface (i.e. footprint); once this is done, the dynamics of the beam are modelled so that the resultant surface is obtained as a convolution of single beam footprints.

2. Modelling approach

2.1. Kinematic modelling of pulsed laser beam

Let $P(t)$ be the power emitted by a pulse laser for a time interval of Δt, with the intensity $I(x,y,t)$, incident on a domain Ω of planar surface (x,y).

$$P(t) = \iint_{\Omega} I(x, y, t)\, dx\, dy \tag{1}$$

If the laser beam is stationary, the spatial ($I_s(x,y)$) and time ($f(t)$ time modulation) variations of $I(x,y,t)$ are independent (Eq. (2)). Thus, the laser fluence $\Phi_s(x,y)$ follows Eq. (3).

$$I(x, y, t) = I_s(x, y)\, f(t) \tag{2}$$

$$\Phi(x, y) = \int_0^{\Delta t} I(x, y, t)\, dt \Rightarrow \Phi_s(x, y) = I_s(x, y) \int_0^{\Delta t} f(t)\, dt \tag{3}$$

In our experiments the time modulation $f(t)$ is well approximated by a unit height triangular pulse and width τ, which theoretically can be obtained through convolution of two rectangular windows (Fig. 1a). For comparison, an ideally box shaped (Fig. 1b) laser pulse $b(t,\tau)$ is also considered. Thus, for N laser shots with frequency ν, the modulation $f(t)$ is given by Eq. (4),

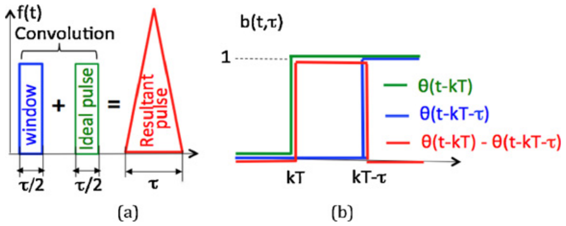

Fig. 1. Real laser pulse $f(t)$ as convolution of rectangular windows (a) and ideal pulse $b(t,\tau)$ as difference of two shifted step functions (b).

with $\theta(t)$ unit step function.

$$f_N(t) = \sum_{k=0}^{N-1} f(t-kT), \text{ where } T = \frac{1}{v} \tag{4a}$$

$$b_N(t) = \sum_{k=0}^{N-1} b(t-kT) = \sum_{k=0}^{N-1} \theta(t-kT) - \theta(t-kT-\tau) \tag{4b}$$

Now, let the laser beam $I(x,y,t)$ travel with a feed speed v_f along the x axis of a reference system R fixed to workpiece (Fig. 2). In this case, the decomposition of $I(x,y,t)$ into a spatial intensity $I_s(x,y)$ modulated by $f(t)$ with respect to R is not trivial, because the spatial x and the time t coordinates are related through v_f, not necessarily constant. However, $I(x,y,t)$ can still be computed in R by first employing the laser beam reference system R′, fixed with respect to the laser beam; in R′ the intensity $I'(x',y',t')$ can be decomposed in spatial $I_s(x',y')$ and time $f(t')$ parts. Then using the Galilean transformations (Eq. (5)) to switch reference frames R and R′, the invariant laser intensity is obtained (Eq. (6)).

$$x' = x - v_f t; \quad y' = y; \quad t' = t \tag{5}$$

$$I(x,y,t) = I(x',y',z') = I_s(x - v_f t, y)\, f(t) \tag{6}$$

Thus, the fluence can be computed (Eq. (7)), for which a full analytical solution cannot be easily derived.

$$\Phi(x,y) = \int_0^{\Delta t} I_s(x - v_f t, y)\, f(t) dt = \frac{\int_0^{\Delta t} \Phi_s(x - v_f t, y)\, f(t) dt}{\int_0^{\Delta t} f(t) dt} \tag{7}$$

In particular, for a single rectangular time pulse $b(t,\tau)$ and a circular laser beam of diameter φ, Eq. (8) is obtained.

$$\Phi_1(x,y) = \int_0^{\tau} I_s(x - v_f t, y) dt = \frac{1}{v_f \tau} \int_{x - v_f \tau}^{x} \Phi_s(x', y) dx' \tag{8}$$

where Φ_s (Eq. (9)) is the fluence of a spot with a diameter φ and known intensity I_s in stationary conditions ($v_f = 0$).

$$\Phi_s(x,y) = I_s \tau \left[1 - \theta\left(x^2 + y^2 - \frac{\varphi^2}{4} \right) \right] \tag{9}$$

2.2. Modelling of (micro)texture generated by a pulsed laser beam with a specified footprint

Let the material response to a single laser spot moving with v_f be given by the profile function $h_1(x,y) = G[\Phi_1(x,y)]$. Then, the surface texture generated by the superposition of N single shots (which could overlap, depending of v_f value) with a period T is $h_N(x,y)$ – Eq. (10); this assumes that there is no interference between two consecutive shots, i.e. the material is cooled instantly and a second pulse will not change the shape of the footprint of the first shot except on the overlapped area.

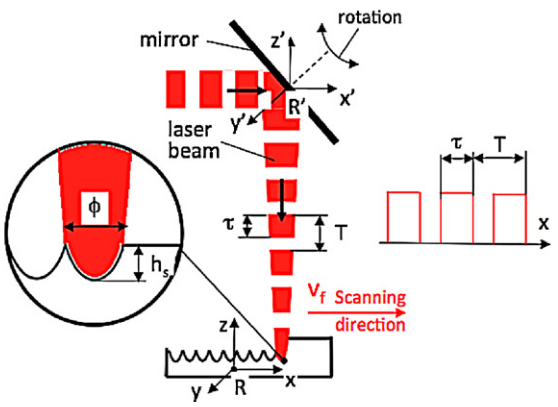

Fig. 2. Generic setup and parameters of PLM.

$$h_N(x,y) = \sum_{k=0}^{N-1} h_1(x - k v_f T, y) \tag{10}$$

Given Eq. (8), the link between the single-shot stationary (h_s) and kinetic profile h_1 is given in Eq. (11), with τ pulse duration and $\Phi_s(x,y) = G^{-1}[h_s(x,y)]$. When profile amplitude h_1 and fluence Φ_1 are proportional, i.e. when G is linear, Eq. (11) becomes Eq. (12).

$$h_1(x,y) = G\left(\frac{\int_0^{\tau} G^{-1}[h_s(x - v_f t, y)]\, f(t) dt}{\int_0^{\tau} f(t) dt} \right) \tag{11}$$

$$h_1(x,y) = \frac{\int_0^{\tau} h_s(x - v_f t, y)\, f(t) dt}{\int_0^{\tau} f(t) dt} \tag{12}$$

For a rectangular pulse, $b(t,\tau) = \theta(t) - \theta(t - \tau)$, Eq. (12) becomes:

$$h_1(x,y) = \frac{1}{v_f \tau} \int_{x - v_f \tau}^{x} h_s(x', y) dx' \tag{13}$$

Using Taylor expansions we get from Eq. (12):

$$h_1(x,y) = h_s(x,y) - \frac{\partial h_s(x,y)}{\partial x} v_f \langle t \rangle + \frac{1}{2!} \frac{\partial^2 h_s(x,y)}{\partial x^2} v_f^2 \langle t^2 \rangle + \cdots \tag{14}$$

where $\langle t^k \rangle$ is the $\langle k\text{th} \rangle$ moment of the distribution $f(t)$:

$$\left\langle t^k \right\rangle = \frac{\int_0^{\tau} t^k f(t) dt}{\int_0^{\tau} f(t) dt} \tag{15}$$

Depending on the model parameters and the shape of pulse modulation $f(t)$, higher order terms could be neglected. When $v_f \tau$ is much less than laser spot diameter φ, an estimated average error, when approximating $h_1(x,y)$ with $h_s(x,y)$, is of the order of:

$$\varepsilon_r = \left| \frac{h_1 - h_s}{h_s} \right| \approx \frac{v_f \tau}{\varphi} < 1 \tag{16}$$

Hence, if we make the approximation in Eq. (17) where the error is of the order of $(v_f \tau/\varphi)^2 \ll v_f \tau/\varphi \ll 1$, and considerably less when we also consider material redeposition [10].

$$h_1(x,y) = h_s(x,y) - \frac{\partial h_s(x,y)}{\partial x} v_f \langle t \rangle \tag{17}$$

Besides the linear response, there is also the well-known 'screening' response of the material when exposed to the laser beam [11]. It can be shown that Eq. (17) still holds in the latter case in the limit $v_f \tau/\varphi \ll 1$. Our experiments correspond to the case when the fluence is well above the material threshold value of $\Phi_L \sim$ 4–4.5 J/cm^2, and therefore $h(x,y) = G(\Phi(x,y))$ is non-linear [11]:

$$h_s(x,y) = \frac{1}{\alpha_L} \ln \frac{\Phi_s(x,y)}{\Phi_L} \tag{18}$$

where α_L is the effective coefficient. For a Gaussian spatially distributed laser intensity $I_S(x,y)$, the stationary single pulse fluence $\Phi_S(x,y)$ is given by:

$$\Phi_s(x,y) = \Phi_s^{\max} \exp\left[\frac{-(x^2 + y^2)}{2\sigma^2} \right] \tag{19}$$

Hence, from Eq. (1), (3) and (19) the maximum ($\Phi_S^{\max}$) and average (Φ_S^{ave}) fluence can be obtained:

$$\Phi_s^{\max} = \frac{P}{2\pi\sigma^2 v}; \quad \Phi_s^{\text{ave}} = \frac{4P}{\pi\varphi^2 v} \tag{20}$$

with P the average power of the laser. According to [12] the average fluence is half the maximum one and hence Eq. (20) gives:

$$\varphi = 4\sigma \tag{21}$$

With Eqs. (19), (21) and 18 becomes:

$$h_s(x,y) = \frac{1}{\alpha_L} \ln \frac{\Phi_s^{\max}}{\Phi_L} - \frac{8(x^2 + y^2)}{\alpha_L \varphi^2} \tag{22}$$