Applied Surface Science 258 (2012) 9309–9313

Contents lists available at SciVerse ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

A simple model for flyer velocity from laser-induced forward transfer with a dynamic release layer

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ARTICLE INFO

Article history:
Available online 7 September 2011

Keywords:
Gurney energy
Flyer velocity
model
LIFT
laser ablation
DRL

ABSTRACT

A simple 1-D model has been developed for the velocity of flyers in vacuum generated by laser-induced forward transfer (LIFT) with a dynamic release layer (DRL). It is an extension of a laser ablation model for metal flyer plates based on the Gurney model of explosive output for driving metal fragments. The model has been extended to the bilayer system of a DRL overlain with a transfer layer. The suitability of the model has been checked with experimental velocity data obtained from shadowgraphy. The experiments used bilayer samples of triazene polymer/aluminium, ablated from the backside through the substrate at reduced pressure (5×10^{-2} mbar). The results suggest that the Gurney energy approach provides the basis of a viable, physically relevant, algebraic model for LIFT, but other loss mechanisms still need be incorporated, particularly thermal loss into the fused silica substrate.

1. Introduction

Laser-induced forward transfer (LIFT) is a technique developing rapidly for patterned deposition of thin films. With the development of a sacrificial dynamic release layer (DRL) to help transfer more sensitive materials [1], recent work has focussed on the deposition of functional materials [2,3]. In particular, we are investigating the use of a triazene polymer (TP) as a DRL [4]. Most of the work in this field has been experimental, but there is a pressing need for theoretical understanding of the multitude of different processes involved in the technique. There is much work into the theory of polymer laser ablation [5,6], but less on the whole transfer process. The shock wave generated when transfer is accomplished in air has been investigated [7,8], and a basic fit of the input laser energy to the flyer velocity has been made [8], but studies have not gone much further.

In this paper we present the adaption of a model developed for single-layer metal pulsed ablation [9] for use with bilayer (DRL/transfer layer) samples. The model is based on work by Gurney into the velocities of fragments from bombs, shells and grenades during the Second World War [10]. Despite the importance of mechanical shock waves in transferring energy from explosives to surrounding munitions cases, Gurney's assumptions were not based on shock mechanics at all. Gurney assumed that: (1) a given explosive will release a fixed amount of energy per unit mass which will all end up as kinetic energy driving the inert material (metal) and the explosive gaseous products; and (2) the gaseous products have a uniform density and a linear one-dimensional velocity profile.

The first assumption means that the efficiency of energy transfer to the metal fragments is consistent regardless of the system geometry, which works as long as there are no significant "end losses" of the gaseous products. The second assumption is for situations where there are opportunities for multiple shock reverberations in the gaseous product space whilst the confinement is still intact [11].

2. Model outline

The basis for this LIFT flyer model is work by Lawrence and Trott [9]. The geometry is standard backside ablation, as used in LIFT [12,3]. This means the laser light pulse goes through a transparent substrate and hits the DRL perpendicular to the plane of the substrate and films, which are assumed to be perfectly parallel to one another. Along with the original Gurney model assumptions stated in Section 1, a number of further assumptions are made. The substrate is assumed to be mechanically rigid with respect to the ablation products, which is reasonable for the 1 mm thick fused silica substrates, relative to the DRL and transfer layer thicknesses of <1 μm. The deposition of the laser energy is assumed to be an approximation of a standard exponential profile con-

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doi:10.1016/j.apsusc.2011.08.111

trolled by an effective optical absorption coefficient μ_{eff} of the DRL, according to Beer–Lambert's law. This effective absorption coefficient is either an empirical value, derived from frontside ablation data (e.g. [4,13]), or it can be calculated from fundamental material properties, as for metals: the linear optical absorption coefficient μ_a of the DRL, the DRL thermal diffusivity α_d, and also the laser pulse length τ (Eq. (5)) [9]. The total absorbed energy is assumed to equilibrate over the ablation depth during the pulse length. The model is 1-D, as stated in Gurney's second assumption in the introduction, which is reasonable for our samples which usually have lateral dimensions ~500 μm, and thicknesses <500 nm.

The bilayer (DRL/transfer layer) structure assumes that the overlying transfer layer ablates at much higher energies than the DRL, and is therefore not ablated at all. This is reasonable, as long as the fluence is not high enough for a large amount of laser energy to impinge on the transfer layer. As soon as all the DRL is ablated we may say that the model stops being valid because of this assumption.

The Gurney model is applied to laser ablation by assuming that the geometry of the ablation represents one half of a "symmetric sandwich" [14,11]. The ablated portion of the DRL replaces the explosive material in the original model, and the substrate interface the symmetry plane. The Gurney energy, on the left hand side of Eq. (1), is equated to the kinetic energy of the flyer and the kinetic energy of the ablation products, on the right hand side of Eq. (1):

$$\rho_d x_d E = \frac{\rho_t x_t + \rho_d (x_0 - x_d)}{2} v_0^2 + \frac{\rho_d}{2} \int_0^{x_d} \left(v_0 \frac{x}{x_d} \right)^2 dx \quad (1)$$

ρ_d is the DRL density, ρ_t is transfer layer density, x_0 is the initial DRL thickness, x_d is the ablated layer thickness, x_t is the transfer layer thickness, v_0 is the initial velocity of the flyer, and E is the Gurney energy (calculated in Eq. (11)). From the second of Gurney's original assumptions outlined in the introduction, the velocity of the ablation products is assumed to follow a linear Lagrangian profile:

$$v(x) = \left(\frac{v_0}{x_d} \right) x \quad (2)$$

Using Eq. (2) the solution to Eq. (1) for the velocity v_0 is:

$$v_0 = \sqrt{\frac{6 E \rho_d x_d}{3\rho_t x_t + \rho_d (3x_0 - 2x_d)}} \quad (3)$$

The Gurney energy E is the total energy transformed into kinetic energy of gaseous products and flyer. This means that it is all the energy inputs minus any loss mechanisms other than kinetic energy, as shown in Eq. (4).

$$E = \text{total input energy} - \text{total energy lost} \quad (4)$$

The input energy comes from two sources: the laser fluence F and the energy from the decomposition reaction of TP ΔH_{dec}. There are four energy outputs defined by the model: the energy in the flyer's kinetic energy, the energy lost in the kinetic energy of the decomposition products, the proportion of input laser energy lost due to reflection r (incorporated in E), and the energy lost below the minimum energy required for ablation ε_0 (incorporated in E). There may be other energy losses in the process, but here we assume that they are all included in the r, and are therefore uniform with respect to the fluence. In order to calculate the laser energy deposition, the effective absorption coefficient μ_{eff} must be determined. Following Lawrence and Trott [9], we can also calculate an effective absorption coefficient by adjusting the true optical absorption coefficient μ_a to take into account thermal diffusion α_d in the film during the laser pulse length τ:

$$\mu_{eff} = \frac{\mu_a}{1 + k\mu_a \sqrt{\alpha_d \tau}} \quad (5)$$

k is included as a correction factor for the thermal diffusivity and absorption coefficients, but here it is always assumed to be 1. The effective absorption coefficient can also be taken from single-pulse ablation depth measurements as a function of fluence. A simple model can be used which assumes that the effective absorption coefficient is constant across all fluences [15,13], or a more complicated fit can be used to allow for different absorptions depending on the degree of (1) linear (ordinary) absorption, (2) excited absorption, and (3) plume (product) absorption [16]. We use the second, variable absorption coefficient in our model, but refer the reader to the article of Mansour and Jamshidi-Ghaleh for further information [16].

Using the calculated effective absorption coefficient, the energy per unit mass (also known as the energy density) deposited by the laser $\varepsilon(x)$ can be calculated as a function of depth using μ_{eff}:

$$\varepsilon(x) = \frac{\mu_{eff} F (1 - r)}{\rho_d} \exp(-\mu_{eff} x) \quad (6)$$

At the substrate/DRL interface ($x = 0$), the deposited energy density is maximum:

$$\varepsilon_0 = \frac{\mu_{eff} F (1 - r)}{\rho_d} \quad (7)$$

The laser energy density is a function of depth, shown in Eq. (6). A minimum energy density parameter ε_d is now created, representing the threshold energy required for ablation. ε_d is also the laser energy density at the ablation depth x_d, and consequently was the decomposition energy required to vaporise the metal in the original model of Lawrence and Trott [9]. However, the triazene decomposition is an exothermic reaction, with a decomposition enthalpy created by the release of the "potential energy" in the chemical bonds ΔH_{dec}. ε_d may be dependent on the activation energy of the DRL decomposition, but it is more complicated and may be thought of, more simply, as an irreversible ablation activation energy.

If the ablation depth is already known, for example from frontside ablation experiments [4,13], ε_d can be calculated from the ablation depth x_d for a given fluence F, using Eq. (8):

$$\varepsilon_d = \varepsilon(d) = \frac{\mu_{eff} F (1 - r)}{\rho_d} \exp(-\mu_{eff} x_d) \quad (8)$$

Perhaps a more useful way to calculate ε_d is from the threshold fluence F_{th}. F_{th} can be either estimated or empirically derived. Eq. (9) is an adaptation of Eq. (7), where $\varepsilon_0 = \varepsilon_d$ because $x_d = 0$ at the threshold fluence:

$$\varepsilon_d = \frac{\mu_{eff} F_{th} (1 - r)}{\rho_d} \quad (9)$$

Using ε_d, the ablation depth can be calculated by rearranging Eq. (8):

$$x_d = \frac{1}{\mu_{eff}} \ln \left(\frac{\mu_{eff} F (1 - r)}{\rho_d \varepsilon_d} \right) \quad (10)$$

We now have all the parameters required for this simple Gurney energy model:

$$E = \frac{F(1 - r)}{\rho_d x_d} + \Delta H_{dec} - \varepsilon_d \left\{ 1 + \frac{1}{\mu_{eff} x_d} \right\} \quad (11)$$

On the right-hand side, the first term is the total available deposited laser energy per unit mass (*input*), the second the enthalpy of decomposition of the triazene (*input*), the third is the threshold (and therefore unused) energy (*output*), and the fourth