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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1063/1.1575495>

Journal of Applied Physics, 93, 12, pp. 9753-9759, 2003

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Geometrical modeling of surface profile formation during laser ablation of materials

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ABSTRACT

Recent advances in the laser machining technology have made it possible to fabricate parts and features with high accuracy and precision, using high-powered, short-pulsed, Q-switched lasers. To determine the machining parameters to obtain desired geometrical quality, an understanding of the relationship between the process parameters and the resulting surface profile, is necessary. In the present study, we adopt a geometrical approach, which coupled with the material properties and machining process parameters, yields a method to determine the surface profile of the material ablated by a laser pulse. It is reasoned that the energy incident upon an infinitesimal area of the surface at a given time is transferred in the outward normal direction to the surface, and the volume of ablation, centered about the normal, is determined by the laser-material interaction and the process parameters. The direction and depth of ablation determine the modified surface profile an infinitesimal time later, yielding a nonlinear partial differential equation, which is then integrated, starting with the initial known surface to determine the profile at an arbitrary time. Theoretical predictions and the experimental results are compared for a test case of metals. The agreement between the two is satisfactory indicating the adequacy of the approach.

I. INTRODUCTION

Availability of high powered, short pulsed lasers, and the technological advances in the related areas of conventional CNC machining have made it possible to machine features with high accuracy and precision,¹⁻⁴ stimulating interest in the underlying processes. The phenomena of significance, which determine the amount of ablated material, depend on the material properties. The response of metals to laser irradiation is largely determined by their thermal diffusion properties. For the dielectrics, which have large band gaps, thermal conduction is essentially absent. Instead, the laser energy is mostly absorbed by the electrons in the conduction band, which then generate more electrons by impact ionization.^{5,6} Initially, a few seed electrons in the conduction band are generated by the low probability phenomenon of multi-photon ionization. Semi-conductors behave somewhere in between, as a consequence of a small band gap. In this case, photo-ionization plays a significant role by generating large number of conduction band electrons, which can effectively transfer heat to the lattice, similar to metals^{7,8,9}.

In case of the single pulse processing of the materials, the pulse width determines the magnitude of the electron-lattice coupling¹⁰⁻¹² impacting upon the response of the material including the quantity of the ablated volume and the surface profile. Material from the dielectrics even with the long pulse lasers is removed directly without passing through the molten phase^{5,6}. The same is the case with the other materials with lasers of pulse-widths in the femtoseconds range. Semiconductors and semimetals pass through the molten phase as the pulse-width reaches nanosecond range⁷⁻⁹ but metals start melting for pulse-widths in the picoseconds range^{11,12}.

The scheme used in the literature to estimate the surface profile is to integrate the velocity front determined by the vapor pressure described by an Arrhenius type equation. This procedure can be legitimately applied when melting is the determining part of the ablation process. However, this scheme is extended heuristically to estimate the profile even when the ablation proceeds directly, where its applicability is questionable. In any case, the accuracy of the profile details obtained by this scheme remains limited¹⁰. In view of the abilities of the current micro-machining techniques, it is desirable to develop procedures to determine the detailed surface profile with compatible accuracy.

In the present article, we describe the evolution of the surface profile with respect to time in more detail from geometrical considerations assuming that the energy available to remove a unit volume of the material can be calculated from the laser material interaction. Thus, the geometrical formulation complements the related schemes. During the material removal phase, the profile of the ablated surface at a given time t is used to determine it at a later time $(t + dt)$, as follows. At time t , the incident laser radiation reflects from the tangent plane to the ablated surface at each of its points, transferring energy into the lattice in the direction of the normal to the tangent surface at that point. This energy interacts with the work piece surface to remove the material. The volume element removed is assumed to be symmetrical about the outward normal to the tangent plane at each point, which determines the evolution of the surface after an infinitesimal increment dt in time. This yields a nonlinear partial differential equation, which is then integrated to obtain the profile of the ablated surface at an arbitrary time, starting with the initial known surface profile.

The geometrical formulation of the surface formation is material independent. Energy available and needed to remove the material depends on the material properties and the laser

material interaction, with varying phenomena of significance, which are coupled with the geometrical formulation. In the present paper, we restrict the consideration of energy needed for material removal to the ablation of metals by lasers of pulse-widths in the nanosecond range, which can be described in terms of the thermal transfer properties^{11,12}. The heat transfer to the metals is quite adequately described by a one dimensional diffusion equation.¹¹⁻¹⁵ This equation is usually used to calculate the temperature distribution in metals. As a test case, we combine the thermal transfer properties of metals with the geometrical formulation of the surface formation, indicated above, to develop a method to describe the geometrical details of the ablated surface more accurately.

In case of metals with nanosecond lasers, melting precedes material removal. Incident optical energy is diffused in the form of heat into the metal, raising the temperature of the surface to the melting point. The diffusion equation describes the heat transfer into the metal adequately until the melting point is reached. A part of the incident energy is then used in melting and evaporating the material. Part of the energy still continues to be lost into the lattice as the melting temperature is maintained at the surface. Material removal terminates when the laser energy is insufficient to melt and evaporate the solid, in addition to sustaining the diffusion. This enables one to calculate the energy available for ablation. The geometrical model supplemented with this information is used to determine the surface profile of the ablated material. For shorter pulse-width lasers and other materials, other relevant phenomena should be taken into account for calculations of the energy needed and available for ablation.

In cases when melting precedes ablation by vaporization, it is desirable to include the pressures and the fluid flow properties of the melt into considerations^{16,17}. However, in craters created by a single pulse of low intensity lasers, the impact of these effects on the surface profile is small, which increases with increasing intensity, as is verified by the results reported in the present article. We have ignored the fluid properties of the melt for the present, as the intensities are not very high as well as for complexity requiring additional developments.

A comparison of the experimentally observed surface profile is made with the theoretical predictions for machining of copper and brass foils by lasers of pulse widths in the nanosecond range, starting with a flat surface. In view of the flatness of the initial surface and the radial symmetry of the laser beam, the equations reduce to a radially symmetric system, simplifying the calculations. Energy distribution in the laser beam was assumed to be Gaussian, both with respect to space and time. Material removal phase was found to start well before the peak power was reached, diffusion during the ablation phase was found to be quite small, and the ablation process was found to continue until the laser power reduced to a small fraction of the peak power. The model is found to describe the statistically averaged observed surface profile quite accurately. Agreement between the experimental observations and the calculated profile is better at lower pulse energy of 25 μJ than at higher pulse energy of 245 μJ where the impact of the fluid flow is noticeable, as expected.

II. GEOMETRICAL FORMULATION OF THE ABLATED SURFACE

The geometrical description of the evolution of the ablated surface with time, developed here, is material independent. The material properties impact upon the energy available and needed for ablation. During the initial phase, the absorbed energy is used to initiate the ablation process beginning at time t equal to $t_{\min}$. In this section, we confine to the evolution of the surface during the ablation phase, $t_{\min} \leq t \leq t_{\max}$, where $t_{\max}$ is the time when the laser energy is

no longer sufficient to maintain the material removal process and losses to the material. For the present test case $t_{\min}$ is the onset of melting, which together with $t_{\max}$, and the energy available during the material removal phase are determined in Sec. III.

Starting with an arbitrary point $P(t) = (x, y, z(x, y, t))$, at time t , on the ablated surface, $S(t)$, the purpose is to determine the corresponding point at an infinitesimal time later. Since the initial surface, is known, this is sufficient to determine the surface at all later times.

The tangent space $T_p(t)$ to $S(t)$ at $P(t)$ is spanned by the basis vectors e_x and e_y , given by

$$e_x = \left(1, 0, \frac{\partial z}{\partial x} \right), \text{ and } e_y = \left(0, 1, \frac{\partial z}{\partial y} \right).$$

To a good degree of approximation, a laser beam incident and reflected at $P(t)$ transfers momentum, and energy, in the direction of the outward normal $\nu(x, y, z(x, y, t))$ to the space $T_p(t)$ at $P(t)$, given by

$$\nu(x, y, z(x, y, t)) = \frac{(e_y \times e_x)}{|(e_y \times e_x)|} = \frac{1}{\eta(x, y, z(x, y, t))} \left(\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}, -1 \right) \quad (1)$$

where $(e_y \times e_x)$ is the vector product of the vectors e_y and e_x , and

$$\eta(x, y, z(x, y, t)) = \sqrt{1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2},$$

is the area enclosed by the vectors e_x and e_y , which projects on the surface element of unit area in the $X - Y$ plane.

Let $I(x, y, t)$ and a_θ be the laser power and the absorption coefficient, where θ is the angle between the reflected beam and the inward normal. The case $\theta = 0$ corresponds to a vertical laser beam incident upon the $X - Y$ plane. The intensity at $P(t)$ from time t to $(t + dt)$ is equal to $[I(x, y, t) dt] / \eta(x, y, z(x, y, t))$, and thus, the absorbed energy per unit area I_{abs} is given by, $I_{abs} = [a_\theta I(x, y, t) dt] / \eta(x, y, z(x, y, t))$. The absorption coefficient also depends on $\theta(x, y, z(t))$, which is assumed to be directly proportional to the transferred momentum, i.e.,

$$a_\theta(x, y, z(x, y, t)) = a_0 \cos(\theta) = a_0 (-\hat{z} \cdot \nu[x, y, z(x, y, t)]) = [a_0 / \eta(x, y, z(x, y, t))],$$

where $\hat{z}$ is the unit vector in the upward vertical direction, and the dot denotes the scalar product. Consequently,

$$I_{abs} = [a_0 I(x, y, t) dt] / \eta^2(x, y, z(x, y, t)).$$

Let $(\Delta j dt)$ be the corresponding energy per unit area lost to the lattice during the material removal phase. The depth of ablation $\sigma(x, y, z(x, y, t), t) dt$ in the direction of the outward normal during the time dt is given by,

$$\sigma(x, y, z(x, y, t), t) dt = \{ [a_0 I(x, y, t) / \eta^2(x, y, z(x, y, t)) - \Delta \mathcal{J}] / E_H \} dt \quad (2)$$

where E_H is the energy required to remove the unit volume of the material.

From Eqs. (1) and (2), the point $P(t + dt) = [P(t) + dP(t)]$, on the surface at time $(t + dt)$, corresponding to $P(t)$, is given by,

$$dP(t) = (dx, dy, dz(x, y, t)) = \alpha(x, y, z(x, y, t)) \left(\frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}, -1 \right) dt \quad (3)$$

where $\alpha(x, y, z(x, y, t), t) dt = [\sigma(x, y, z(x, y, t), t) dt] / \eta(x, y, z(x, y, t))$.

Hence,

$$\frac{dx}{dt} = \alpha(x, y, z(x, y, t), t) \frac{\partial z}{\partial x}, \quad \frac{dy}{dt} = \alpha(x, y, z(x, y, t), t) \frac{\partial z}{\partial y},$$

and

$$\frac{dz}{dt} = \left[\frac{\partial z}{\partial t} + \frac{dx}{dt} \frac{\partial z}{\partial x} + \frac{dy}{dt} \frac{\partial z}{\partial y} \right] = -\alpha(x, y, z(x, y, t), t),$$

i.e.,

$$\frac{\partial z}{\partial t} = -\alpha(x, y, z(x, y, t), t) \left[\left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 + 1 \right] \quad (4)$$

Appropriate substitutions from Eqs. (1), (2) and (3), into Eq. (4), yield the following equation for the time evolution of the ablated surface:

$$\frac{\partial z}{\partial t} + \frac{a_0 I(x, y, t)}{E_H} \left[1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right]^{-\frac{1}{2}} - \frac{\Delta \mathcal{J}}{E_H} \left[1 + \left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right]^{\frac{1}{2}} = 0 \quad (5)$$

The surface profile is obtained by solving Eq. (5), for t from $t_{\min}$ to $t_{\max}$ with $z(x, y, t_{\min})$ being the initial, known, profile.

III. THERMAL DIFFUSION

To determine the surface profile from Eq. (5) one needs the values of $t_{\min}$, $t_{\max}$, $\Delta \mathcal{J}$ and E_H . Procedures to determine these quantities for the ablation of metals with nanosecond lasers are described below using the thermal diffusion properties of the metals.

The evolution of the temperature for $t < t_{\text{melt}} = t_{\min}$, in response to the laser irradiation, is governed to a good degree of approximation by the one dimensional thermal diffusion equation,^{10,11,12} which in the nanosecond regime reads^{8,9,10} as,

$$\begin{aligned} \frac{\partial T_{\zeta}}{\partial t} - \frac{\partial}{\partial \xi} D \frac{\partial T_{\zeta}}{\partial \xi} &= \frac{I(x, y, t) a_0 \alpha}{C} \exp(-\alpha \xi) \\ T_{\zeta}(\xi, -\infty) &= 0, \quad T_{\zeta}(\infty, t) = 0, \quad \frac{\partial T_{\zeta}(\xi, t)}{\partial \xi} = 0 \quad \text{at} \quad \xi = 0, \end{aligned} \quad (6)$$

where $T_z(\xi, t)$ is the electron temperature at location ξ along the normal to the appropriate surface, which during this phase is the initial surface. For a flat surface, ξ is the coordinate representing the vertical direction with the origin at the surface. In Eq. (6), D , C and α are the diffusivity, electron specific heat, and the inverse of the optical absorption depth of the material, respectively, and the laser power, is given by,

$$I(x, y, t) = I_0 \exp[-2(x^2 + y^2)/(D_B/2)^2 - \kappa(t/\tau_p)^2] \quad (7)$$

where $\kappa = 4\log(2)$, τ_p is the pulse width, I_0 is the peak power reached at the center of the beam at zero time, and D_B is the beam diameter.

In the present long pulse regime the electron and the lattice temperatures are almost equal, reducing the general diffusion equation^{10,11,18} to Eq. (6). Also, the diffusion function D , although not constant at high temperatures, it is assumed to be constant for the present. This approximation is quite adequate within the degree of the accuracy of the experimental data available.

With these simplifying assumptions, the solution of Eq. (6) is given by,

$$\begin{aligned} T_z(\xi, t) &= \frac{a_0 \alpha}{C} \int_0^\infty dk \cos(k\xi) \frac{\alpha}{(\alpha^2 + k^2)} \int_{-\infty}^t dt' \exp[-Dk^2(t-t')] I(t') \\ &= \frac{a_0 \alpha}{C} \int_0^\infty dk \cos(k\xi) \frac{\alpha}{(\alpha^2 + k^2)} \int_0^\infty d\tau \exp[-Dk^2\tau] I(t-\tau) \end{aligned} \quad (8)$$

where $\tau = (t - t')$. It can be shown that $T_z(\xi, \infty) = 0$, in addition to the given condition, $T_z(\xi, -\infty) = 0$, which in turn can be used to express the plane wave Fourier transform $\hat{T}_z(\xi, \omega)$ of $T_z(\xi, t)$ as,

$$\hat{T}_z(\xi, \omega) = \frac{I_0 a_0 \exp[-\omega^2/(4\kappa)]}{C\sqrt{2\kappa} (D\alpha^2 + i\omega)} \left[\alpha(i+1) \sqrt{\frac{D}{2\omega}} \exp[(i-1)\sqrt{\frac{\omega}{2D}} \xi] - \exp(-\alpha\xi) \right] \quad (9)$$

where ω is the conjugate variable with respect to t . The temperature $T_z(\xi, t)$ is determined by $\hat{T}_z(\xi, \omega)$, as its inverse Fourier transform, which determines t_{melt} from $T_z(0, t_{melt}) = T_{melt}$.

For $t > t_{melt}$, the laser energy is used in melting and evaporating the material with the temperature at the surface of the ablated region maintained at T_{melt} . Since the material above the bottom of the melt absorbs the laser energy, there is no source of heat below it. Hence the heat diffusion in the material below the melt is governed by,

$$\begin{aligned} \frac{\partial T_z}{\partial t} - \frac{\partial}{\partial \zeta} D \frac{\partial T_z}{\partial \zeta} &= 0, \quad t \geq t_{melt}, \quad \zeta \geq 0, \\ T_z(0, t) &= T_{melt}, \quad T_z(\infty, t) = 0. \end{aligned} \quad (10)$$

In Eq. (10), ζ is the coordinate along the outward normal to the ablated surface with the origin at the bottom of the melt, which defines a variable boundary. However, the effects of the

variable boundary, detailed description of the thermal transfer inside the liquid metal, and similar effects at the vaporization phase, will be neglected for the present.

To uniquely define the solution of Eq. (10), one boundary condition with respect to time is also needed, which is determined as follows. Let $\xi(\zeta)$ be the value of ξ for a given ζ , both coordinates placed along the same axis. We assume that

$$T_{<}(\xi(0), t_{melt}) = T_{<}(0, t_{melt}) = T_{melt},$$

which is a mild assumption in view of the fact that the temperature gradient at $\xi = 0$ for $t \leq t_{melt}$ is equal to zero. This assumption is also consistent with neglecting the effects of the variable boundary. Essential equivalence of ξ and ζ implied by this assumption, also requires rotation symmetry of $T_{<}(\xi, t)$ in the neighborhood of the ablated region, which is justified by the validity of the one dimensional diffusion model. With these assumptions, the additional condition is given by,

$$T_{>}(\zeta, t_{melt}) = T_{<}(\xi(\zeta), t_{melt}) \quad (11)$$

The solution of Eq. (10) is now given by

$$T_{>}(\zeta, t) = T_{<}(\xi(\zeta), t_{melt}) + \frac{2}{\pi} \int_0^{\infty} \frac{dk}{k^2} \sin(k\zeta) (1 - \exp[Dk^2(t_{melt} - t)]) \ddot{T}_{<}^{sf}(k), \quad (12)$$

where $\ddot{T}_{<}^{sf}(k) = \int_0^{\infty} d\zeta \sin(k\zeta) \frac{\partial^2 T_{<}(\xi(\zeta), t_{melt})}{\partial \zeta^2}$

The heat flux $\Delta J(\zeta, t)$ is determined by $T_{>}(\zeta, t)$:

$$\Delta J(\zeta, t) = -CD \frac{\partial T_{>}(\zeta, t)}{\partial \zeta} \quad (13)$$

Thus, the heat flux $\Delta J = \Delta J(0, t)$ into the material during the material removal phase is given by,

$$\Delta J(0, t) = -\frac{2CD}{\pi} \int_0^{\infty} \frac{dk}{k} (1 - \exp[Dk^2(t_{melt} - t)]) \ddot{T}_{<}^{sf}(k) \quad (14)$$

The ablation process ceases when ΔJ exceeds the supplied heat. Thus, t_{max} is determined by,

$$a_0 I(x, y, t_{max}) = \eta^2(x, y, z(t_{max})) \Delta J(0, t_{max}) \quad (15)$$

IV. RESULTS AND DISCUSSION

Present model was tested by comparing the theoretical predictions with the experimental observations of the surfaces of the craters produced by laser machining of brass and copper foils. Thin foils of copper and brass with thickness of 70 μm were mounted on a specially built vacuum fixture, which was equipped with features to remove any surface distortions, striations and unevenness while loading. All the experiments with copper foils were carried out using an electro-optically Q-switched diode pumped solid state laser HPO-1000 (by Continuum Inc.) which has pulse width of 9.8 ns, wavelength of 532 nm and a shot-to-shot stability of 95.0% for TEM00 mode and an appropriate beam delivery system. The AMOCO OEM 1064-1000Q laser by AMOCO Laser Company was used to machine the brass foils. This laser has a pulse width

of 16.2 ns at a pulse repetition rate of 1.0 kHz with a wavelength of 1064 nm and pulse to pulse instability of less than 6.5% for linear polarization and TEM00 mode. Different lasers were used to determine the effects of the laser properties on the surface profile. The positioning accuracy of the motion system was of the order of 0.5 μm in the X and Y - axes. The pulse energy measurements were carried out using a calibrated laser power meter (model: TMP-300 from Gentec Inc). A single laser pulse creates a bowl-like crater on the foil. The distance between craters was set at greater than 30 μm to avoid overlapping of the heat-affected zones. An optical microscope and a WYKO surface profilometer were used to measure the crater geometry and the surface topology on the machined foils. An example of the typical laser machined craters and the corresponding X and Y profiles of the ablated surface for a brass foil are shown in Figure 1.

For comparison with the theoretical values calculated for a radially symmetric system, the profile depths along X and Y - axes were averaged to obtain the profile with respect to the radial distances. Also, the data for comparison was taken to be the average over a number of measurements carried out to minimize the effects of statistical variations. The statistical deviations were used to determine the surface profile within the experimental accuracy.

The laser power distribution was assumed to be Gaussian, both in space and time, given by Eq. (7), with the peak power I_0 determined by

$$\begin{aligned} E_{pulse} &= I_0 \int_{-\infty}^{\infty} dt \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \exp[-2(x^2 + y^2)/(D_B/2)^2 - \kappa(t/\tau_p)^2] \\ &= \frac{1}{8} \pi D_B^2 I_0 \tau_p \sqrt{\frac{\pi}{\kappa}} \end{aligned} \quad (16)$$

where $\exp(\kappa) = 16$.

The temperature $T_c(\xi, t)$, determined by Eq. (9), was computed using the standard Fast Fourier Transform routine. Time evolution of $T_c(\xi, t)$ for copper with $E_{pulse} = 225 \mu\text{J}$ is shown in Figure 2. The temperature on the surface rises quickly after the irradiation starts, reaching the melting point at $t_{melt} = -1.03$ in units of the pulse-width, i.e., by the time the laser power has increased from zero to about 1/16th of its peak power. The normalized heat flux $\Delta j' = \Delta j/(a_0 I_0)$ with Δj given by Eq. (14), is plotted in Figure 3, which shows that the energy lost to the material during the material removal phase is negligible, as is normally assumed in the literature. As expected, inclusion of the heat flux $\Delta j = \Delta j(0, t)$, and setting the upper limit for time equal to t_{max} makes no noticeable impact on the calculated surface profile.

Initial surface of the foils was assumed to be flat in conformity with the visual observations. This together with the radial symmetry of the laser beam implies the radial symmetry of the depth parameter z . Further neglecting the second term, which is proportional to Δj , reduces Eq. (5) to

$$\frac{\partial z(r)}{\partial t} = - \frac{a_0 I(r, t)}{E_H} \left[1 + \left(\frac{\partial z(r)}{\partial r} \right)^2 \right]^{-\frac{1}{2}} \quad (17)$$

where r is the radial distance with origin at the center of the laser beam. The right side in Eq.

(17) was evaluated by forward differencing with respect to the radial distance r , and $z(r)$ was evaluated by the forward Euler method starting at t_{melt} . Since the melting temperature is reached quite quickly after the irradiation begins, it was found that integrating Eq. (17) from $t = -\infty$, instead of t_{melt} , does not change the predicted profile significantly.

Theoretical predictions and the experimental observations are displayed in Figure 4 for copper, and in Figure 5 for brass with laser specifications as indicated. There are noticeable statistical variations in the experimental data. The observations selected are deemed to represent the observed profiles adequately. Since the representative experimental profile is obtained by averaging the X and Y profiles, it is radially symmetric. Also there are significant cancellations between the statistical variations yielding a smoother profile than the individual craters. Also, the rim at the edge of the craters formed by the flow in the melt was found to average out to an insignificant amount for low energies but was found to be noticeable for higher energies, presumably resulting from the fact that the flow is higher at higher temperatures. Such variations are outside the scope of the present model.

From Figs. 4 and 5, the agreement between the theoretical and the statistically averaged experimental values of this set of observations, for different lasers and materials, is quite good, indicating the adequacy of the geometrical approach to formulate the laser pulse ablated surfaces of metals. At higher pulse energy, the agreement is less satisfactory at the rim of the crater. A more accurate description would require inclusion of the fluid behavior in the melt.

V. CONCLUDING REMARKS

We have developed a mathematical model to determine the detailed geometrical profile of the surface of the materials ablated by lasers, which has received little attention in the literature. The present approach combines the laser-material interaction properties with the geometrical properties of the surface to determine its evolution with respect to the time. The geometrical formulation is independent of the material and the laser specifics, which determine the amount of heat needed and available for material removal. Thus the geometrical formulation presented here is applicable to study the surface profiles of essentially all materials irrespective of the laser used.

For comparison with the experimental observations, the foils of brass and copper with flat surface were machined with lasers of pulse widths in the nanosecond range. The pulse width, together with the material properties, determines the diffusion equation that adequately describes the heat transfer into the material and the material properties determine the volume of the metal melted and evaporated during a given time period. The geometrical considerations are used to determine the axis about which the ablated volume is located. In the cases considered, the agreement between the theoretical predictions and the experimental observations is quite satisfactory, indicating the adequacy of the present geometrical formulation to describe the surface profile of the laser machined materials.

Present model can be improved further in several ways. The geometrical formulation to determine the surface profile is quite complete, but the calculations of the energy needed will require considerations of the response of a particular material to the laser irradiation. The simplifying assumptions made in case of the present test case pertain to the calculations of the energy needed and available to melt and evaporate the metals, which although mild, may be investigated further. In particular, the initial surface often is not flat enough to justify the assumption of radial symmetry. Thus, an extension of the model to two dimensions is

desirable. Thermal behavior of the melt is ignored in the present treatment, which has more significant impact at higher temperatures, i.e., at higher pulse energies. This expected behavior is consistent with the observations reported in Figure 4 and Figure 5. In view of the degree of agreement between the theoretical and experimental values, the thermal behavior of the melt appears to have little effect on the ablation properties in the present case. However, this phase is likely to have significant impact on the final finish of the re-solidified surface at higher pulse energies, where the temperature dependence of the diffusivity may also have a significant impact on the shape and size of the craters. A formulation that includes the melt will be considerably more complex than the present one. For the test case considered here, the calculations of the energy needed for material removal are reasonably accurate that is necessary to verify the adequacy of the geometrical model, which is the main objective of the present study.

ACKNOWLEDGEMENTS

Thanks are due to Moe Islam, Director, Production Technology Research, IMTI-NRC, for his continued support in this work. Also, the authors are grateful to Kuljit Virk for computational assistance, and to Hugo Reshef and Craig Dinkel, for help in the experimental work.

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List of figure captions

Fig. 1. Typical laser machined craters and the corresponding profiles of the ablated surface of brass foils with lasers of pulse-width = 16.2 ns , wavelength = 1064 nm and pulse energy = $25 \text{ }\mu\text{J}$.

Fig. 2. Evolution of temperature with time prior to the melting point at the surface of copper irradiated with lasers of pulse-width = 9.8 ns , wavelength = 532 nm and pulse energy = $245 \text{ }\mu\text{J}$.

Fig. 3. Normalized heat flux into copper foil during the post-melting phase irradiated with lasers of pulse-width = 9.8 ns , wavelength = 532 nm and pulse energy = $245 \text{ }\mu\text{J}$.

Fig. 4. Comparison of theoretical and experimental copper surface profiles machined with lasers of pulse-width = 9.8 ns , wavelength = 532 nm and pulse energy = $245 \text{ }\mu\text{J}$.

Fig. 5. Comparison of theoretical and experimental brass surface profiles machined with lasers of pulse-width = 16.2 ns , wavelength = 1064 nm and pulse energy = $25 \text{ }\mu\text{J}$.

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.