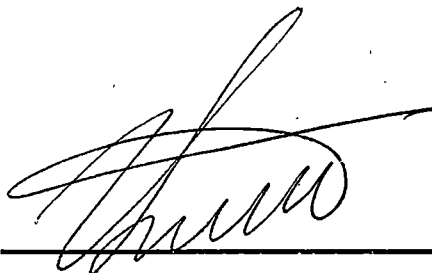


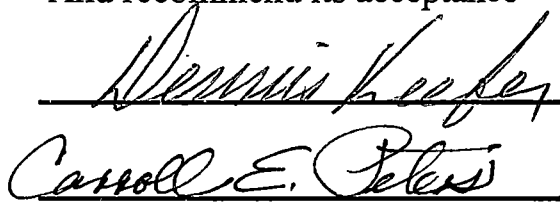
To the Graduate Council:

I am submitting herewith a thesis written by Junlong Zhao entitled "Numerical Simulation of High Intensity Laser Drilling of Metals." I have examined the final copy of the thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.



Dr. Vladimir V. Semak, Major Professor

We have read this thesis
And recommend its acceptance



Accepted for the Council:



Associate Vice Chancellor and
Dean of the Graduate School

**Numerical Simulation of High Intensity
Laser Drilling of Metals**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Junlong Zhao

August 1999

DEDICATION

This thesis is dedicated to my mother,

Mrs. XiaoNing Jin.

She is the most devoted mom in the world.

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ABSTRACT

The objective of this study is to build an effective computer program to simulate high beam intensity laser drilling of metals. The study consists of four parts. In the first part, laser history and laser drilling simulation history are reviewed. In the second part, the mathematical formulation is described, the physical model of laser drilling is discussed and the simulation method is described. In the third part, the simulation parameters are selected and simulation results are analyzed, then the calculation result is compared with a GE experiment result, which shows the simulation is successful. In the fourth part, some conclusions are collected and recommendations for future programming are made.

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NOMENCLATURE

A	absorption coefficient
$A(M_1)$	ambient pressure dependent coefficient
c	speed of light or specific heat
E	energy
$\vec{E}$	electric field
f_0, f_1, f_+, f_-	functions in determining recoil pressure
$\vec{H}$	magnetic field
I	energy flux per unit area
I_a, I_{abs}	absorped energy flux
I_R	reflected energy flux
k	thermal conductivity
k_B	Boltzmann's constant
L_v	latent energy of evaporation
L_m	latent energy of melting
M	atomic mass
M_1	Mach number
n	refractive index
n_1	refractive index of medium
n_2	extinction coefficient

P	pressure
P_r	recoil pressure
P_0	saturation pressure
Q	heat production
R	reflectance coefficient
T	temperature
T_b	boiling point temperature
$T(i, k)$	temperature at grid
t	time
V	velocity
v_x, v_y, v_z	velocity components
v_d	drilling velocity
v_m	melting velocity
v_{dv}	drilling velocity due to evaporation
v_{dm}	drilling velocity due to melting
x, y, z	coordinate
α	absorption coefficient or angle between normal to the surface and laser beam axis
ω	angular frequency
λ	wavelength
μ	viscous coefficient

ϵ_0 dielectric constant in vacuum

γ incidence angle

ρ density

Chapter 1

Introduction

Shortly after invention of the laser in 1960, industry started using it for processing of materials. One of the first applications was drilling of a razor blade by ruby laser used in production by the Gillette company in the early 1960s. In time, the laser's power increased, and its applications in industry became widespread. At the present time nearly all production areas have laser applications, from airplane engines to earring holes, from laser printers to automobile transmissions. It would be hard to imagine the world without laser applications.

Laser drilling is one of the most important industrial applications. Material removal rate, thickness of the recast layer and size of the heat affected zone are some of the important engineering parameters. All these parameters are determined by the mechanisms of interaction between the material and the laser beam. In order to predict these parameters, we need to build an adequate model for the mechanisms of laser material drilling.

The first industrial lasers were ruby and Nd-glass lasers with typical pulse duration of 1~10 ms, intensity of 10^6 W/cm^2 and pulse energy of 1~100 J. Evaporation was suggested as a mechanism for material removal.

Estimations based on an energy conservation approach explained observed results reasonably well. For example, for a Nd-YAG laser with 50 J, 1ms pulse to drill a 3 mm deep, 300 μm wide hole, the estimated absorbed

energy is $E = m(cT_b + L_v + L_m)$

$= 7 \text{ g} / \text{cm}^3 \cdot 7 \cdot 10^{-4} \text{ cm}^2 \cdot 0.3 \text{ cm} (0.6 \text{ J/gK} \cdot 3000 \text{ K} + 5000 \text{ J/g} + 300 \text{ J/g}) \approx 10 \text{ J}$, which requires an absorption coefficient equal to $10 \text{ J} / 50 \text{ J} = 0.2$. This is a pretty reasonable value.

Then TEA CO_2 lasers were developed in the 1970s. The evaporation dominant idea met a serious problem. For example, for TEA CO_2 laser with 0.5 J, 30 μs pulse to drill 0.7 mm deep, 150 μm wide hole, using the evaporation method demanded absorbed energy

$E \approx 7 \cdot 10^{-5} \text{ g} \cdot 7 \cdot 10^3 \text{ J/g} \approx 0.5 \text{ J}$, which requires an absorption coefficient value to 1. In fact, even the most absorbing material could not achieve a perfect absorption coefficient. Therefore, an alternative mechanism for material removal had to be suggested. Von Allmen [1] suggested evaporation recoil driven melt flow as an alternative mechanism. Von Allmen's model is an analytical steady state model that assumes piston-like material ejection.

At approximately the same time, Q-switched Nd:YAG lasers and ruby lasers were quickly developed. Pulse duration of $1ns \sim 100ns$ and high intensity greater than $10^8 W/cm^2$ could be achieved with such lasers. Due to the short pulse duration and high intensity, evaporation is a dominant mechanism for material removal. Anisimov's model [2] can be successfully applied to simulate this drilling. The repetition rates for these lasers were still small, and therefore industrial drilling was impractical.

Recently, Q-switched lasers with high repetition rate (~ 4 KHz) have been developed. Copper vapor lasers with a repetition rate of about 20 KHz and relatively high pulse energy (about 20 mJ) have also been developed. These high repetition rate, high pulse energy lasers can drill a hole in reasonably short time (several seconds) in a metal sample with a thickness of several millimeters. Thus, it became practical to use such lasers in production.

However, only one dimensional models that do not consider deep crater formation and the related effects of multiple reflections on the distribution of absorbed intensity are currently available. The goal of this thesis is to develop a model which can simulate the actual situation.

Chapter 2

Approach Description

2.1 Physical model

2.1.1 Absorption of radiation

The simplest form of light is a monochromatic, linearly polarized plane wave. This will, for most of our purposes, be a sufficient approximation of a real laser beam. The electric field of a wave propagating in a homogeneous and nonabsorbing medium can be represented as

$$\vec{E} = \vec{E}_0 \exp[i(\frac{2\pi z}{\lambda} - \omega t)] \quad (2.1)$$

where z is the coordinate along the direction of propagation, ω is the angular frequency, and λ is the wavelength. The last two quantities are related through the phase velocity c/n_1 , c being the speed of light and n_1 the refractive index of the medium by

$$\lambda = (2\pi / \omega)(c / n_1) \quad (2.2)$$

An expression analogous to (2.1) also holds for the magnetic field H .

Magnetic and electric field amplitudes are related by

$$H_0 = E_0 n_1 \epsilon_0 c \quad (2.3)$$

with ϵ_0 being the dielectric constant in vacuum. On average, the electric and magnetic fields each carry the same amount of energy. [1]

The energy flux per unit area of the wave is termed irradiance and given by

$$I = |\vec{E} \times \vec{H}| = n_1 \epsilon_0 c E_0^2 \quad (2.4)$$

The concept of a beam implies that the irradiance is maximum near the optical axis and falls off laterally. The most common lateral distribution is a cylindrically symmetric Gaussian

$$I(r) = I_0 \exp(-r^2 / w^2) \quad (2.5)$$

where I_0 is the irradiance on axis, and w is referred to as the beam radius.

The total power of the beam is then

$$P = \pi w^2 I_0 \quad (2.6)$$

In absorbing media the real refractive index n_1 must be replaced by a complex index $n = n_1 + in_2$. The meaning of n_2 (also called the extinction coefficient) becomes apparent when (2.2) is accordingly modified and inserted into (2.1): The electric field, upon propagation over a distance z , now decreases by a factor $\exp(\omega n_2 z / c)$, indicating that some of the light energy is absorbed. The absorption coefficient for the irradiance (2.5) is

$$\alpha = -(1/I)(dI/dz) = 2\omega n_2 / c = 4\pi n_2 / \lambda \quad (2.7)$$

The inverse of α is referred to as the absorption length.

The ratio R of reflected to incident irradiance is given by the Fresnel expression,

$$R = \left| \frac{n-1}{n+1} \right|^2 \quad (2.8)$$

The reflectance and the absorption coefficient determine the amount of beam power absorbed within the material. [1]

In opaque materials, where the material thickness is much larger than absorption length, the fraction of energy absorbed is determined by the quantity $(1-R)$ alone, also known as the absorptance.

$$A = 1 - R \quad (2.9)$$

$$I = (1 - R)I_0 \exp(-\mu Z) \quad (2.10)$$

2.1.2 Evaporation

Usually both melting and evaporation occur simultaneously under conditions typical for laser experiments, since the latent heat of vaporization is much larger than that of fusion (typically, by a factor of 20-50 times). Thus, evaporation plays the most important part in the energy balance. [2]

In this thesis, we simulate the interactions of laser radiation with matter at moderate laser intensities. At these intensities, the temperature is usually well below the thermodynamic critical point of the material. Under this condition, a sharp boundary exists between the condensed and gaseous phases, its thickness being on the order of the interatomic distance, and

the density of the vapor is several orders of magnitude less than in the condensed phase. In the majority of cases of practical interest, light absorption in the vapor is relatively small. To simplify the case, we assume that the evaporation occurs in vacuum and the vapor does not absorb the laser radiation.

When the vapor plume does not absorb the laser light, the processes in the condensed and gaseous phases can be considered separately. We will describe the temperature field in the condensed phase by the heat conduction equation

$$\rho c \frac{\partial T}{\partial t} = \text{div}(k \nabla T) + Q(r, t) \quad (2.11)$$

where T is the temperature, k is the thermal conductivity, c is the specific heat, ρ is the density, and $Q(r, t)$ is the heat production (per unit volume per unit time) due to the absorbed laser radiation. In the general case, c and k are temperature dependent, and the above equation is nonlinear.

For metals, however, at temperatures above the Debye temperature, c and k can be taken as constants. [2]

The vaporization of condensed matter cannot be described, even in a very rough approximation, in terms of the "problem of Stefan" with a fixed phase transition temperature. Actually, a solid(liquid) evaporates at any temperature not equal to 0 K. The evaporation rate strongly depends on

the temperature. This dependence, in the case under consideration, can be written in the form:

$$V_n = V_0 \exp(-U/T) \quad (2.12)$$

where V_n is the normal component of the evaporation front velocity,

$U = ML_v / k_B$, L_v is the latent heat of vaporization (per unit mass), k_B is

Boltzmann's constant, M is the atomic mass, and V_0 is a constant whose value is of the order of the speed of sound in the condensed phase. [2]

2.1.3 Generation of recoil force and related melt motion

A condensed phase evaporates at any temperature exceeding 0 K.

Evaporated atoms leave the surface having some momentum. The law of conservation of momentum requires that the surface has the same amplitude but opposite momentum. If the flux of the evaporated atoms is known, then evaporation recoil pressure is a product of the flux and the average momentum of the evaporated atom. Because of collisions part of the evaporated atoms develop a component of velocity toward the surface. This back-flux adds to the recoil pressure. When the surface temperature is low, the vapor atoms leave the near-surface area due to diffusion. A large part of the evaporated atoms returns to the condensed phase. Then the recoil force calculation requires detailed solution of kinetic and diffusion equations. However, in this case the evaporated atoms have small average momentum and the recoil force is negligibly small. In a

majority of practical applications of lasers for material processing, high surface temperatures are reached. If the surface temperature is close to or exceeds the boiling temperature, then a relatively high velocity gas-dynamic flow of vapor is established, and the recoil pressure can not be neglected. The evaporated atoms have a non-Maxwellian distribution function. After several collisions, which occur in a layer with a thickness of several mean free paths, an equilibrium Maxwellian distribution function is established. This new distribution function corresponds to a gas dynamic flow of the vapor. The general scheme of the vapor flow in the case of high surface temperatures is shown in Figure 2.1.

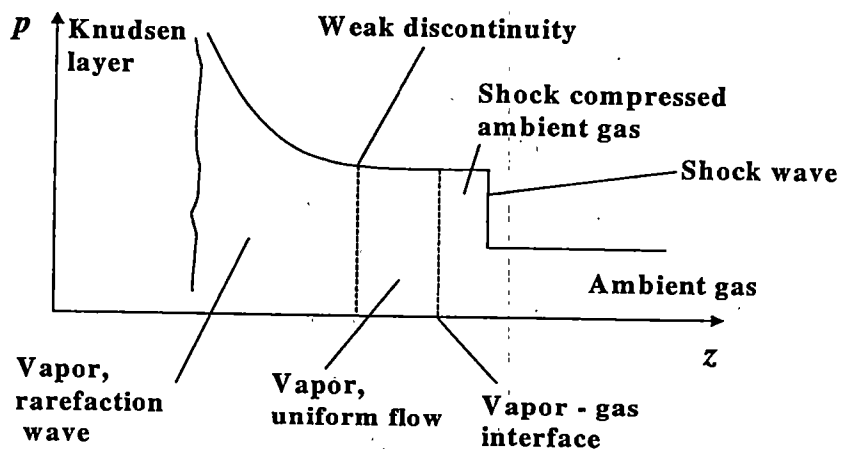


Figure 2.1. Schematic of surface evaporation

The flow to the right from the Knudsen layer is described by gas dynamics equations. The solution for the one-dimensional flow is well known [6]. The gas dynamics solution must be “connected” to the solution of transport equations in the Knudsen layer. This provides the value of vapor flow Mach number at the outer boundary of the Knudsen layer [7]. In the consideration below it is assumed that the gas-dynamics equations are solved and the Mach number is known.

Consider the steady state evaporation of a condensed phase into a vacuum. Let us assign subscripts “0” and “1” to the surface and end of the Knudsen layer, correspondingly, and choose the coordinate frame connected to the evaporating surface with x-axis perpendicular to the surface and with positive direction into the vapor. It is generally accepted [8] that the evaporated atoms entering the Knudsen layer have a Maxwellian distribution function for the positive component of velocity normal to the surface, $v_x > 0$, with number density $n_0(T_0)$ equal to the density of the saturated vapor at surface temperature T_0

$$f_+ = n_0(T_0) \left(\frac{m}{2\pi kT_0} \right)^{3/2} \exp \left(-\frac{m}{2kT_0} (v_x^2 + v_y^2 + v_z^2) \right), v_x > 0 \quad (2.13)$$

The flow of vapor exiting the Knudsen layer has an equilibrium Maxwellian distribution function

$$f_1 = n_1 \left(\frac{m}{2\pi kT_1} \right)^{3/2} \exp \left(-\frac{m}{2kT_1} ((v_x - u_1)^2 + v_y^2 + v_z^2) \right) \quad (2.14)$$

The flow parameters n_1 , u_1 , and T_1 at the end of the Knudsen layer are unknown and must be determined. As mentioned above, we assume that the flow velocity, u_1 , at the end of the Knudsen layer can be determined from the gas dynamics solution, and with this consideration it is assumed known,

$$u_1 = M_1 c_s(T) = M_1 \sqrt{\frac{\gamma kT_1}{m}} \quad (2.15)$$

where M_1 is the Mach number, and c_s is the speed of sound at the end of the Knudsen layer.

In the case of evaporation into vacuum the picture shown in Figure 2.1 is reduced to only the rarefaction wave. Then, in accordance with the Jouguet condition, the flow velocity at the end of the Knudsen layer is equal to the

$$\text{local speed of sound, } u_1 = \sqrt{\frac{\gamma kT_1}{m}}.$$

In this approach one obvious complication arises: we know the distribution function of the atoms evaporated from the surface, f_+ ; however, the distribution function of the atoms returning to the condensed phase from the vapor, f_- , is unknown. To determine f_- one has to solve Boltzmann's equations. However, it is possible to guess this distribution function.

Following a method suggested by Tamm [9] and Mott-Smith[10] one can suggest that the returning particles have a distribution function similar to that at the end of the Knudsen layer. Thus,

$$f_0 = \begin{cases} f_+ = n_0(T_0) \left(\frac{m}{2\pi kT_0} \right)^{3/2} \exp\left(-\frac{m}{2kT_0} (v_x^2 + v_y^2 + v_z^2) \right), & v_x > 0 \\ f_- = \beta f_1, & v_x < 0 \end{cases} \quad (2.16)$$

$$f_1 = n_1 \left(\frac{m}{2\pi kT_1} \right)^{3/2} \exp\left(-\frac{m}{2kT_1} ((v_x - u_1)^2 + v_y^2 + v_z^2) \right) \quad (2.17)$$

It is important that in order to determine the unknown parameters n_1 , T_1 , and β we do not need to solve the Boltzmann's equation. It is sufficient to use the fact that the flow is stationary and the conservation laws of mass, momentum, and energy fluxes hold within the discontinuity region. Thus,

$$\int v_x f_0(\vec{v}) d\vec{v} = \int v_x f_1(\vec{v}) d\vec{v} \quad (2.18)$$

$$\int v_x^2 f_0(\vec{v}) d\vec{v} = \int v_x^2 f_1(\vec{v}) d\vec{v} \quad (2.19)$$

$$\int v_x v^2 f_0(\vec{v}) d\vec{v} = \int v_x v^2 f_1(\vec{v}) d\vec{v} \quad (2.20)$$

Equations (2.15) to (2.20) form a set of coupled equations for the calculation of the flow parameters at the end of the Knudsen layer and the constant β . For the particular case of evaporation in vacuum when $M_1 = 1$, according to Anisimov's calculations [11],

$$\beta=6.29; \quad T_1 = 0.67 T_0; \quad n_1 = 0.31 n_0(T_0) \quad (2.21)$$

The pressure at the end of the Knudsen layer is $p_1 = n_1 k T_1$, and the total momentum $P = p_1 + m n_1 u_1^2 = n_1 k T_1 (1 + \gamma M_1^2)$. For evaporation in vacuum $M_1 = 1$ and using relations (2.21) we obtain $P = 0.55 p_0(T_0)$, where $p_0(T_0)$ is the saturation pressure corresponding to the surface temperature T_0 . The total momentum equals the recoil pressure, p_r , applied to the surface. Thus, $p_r = 0.55 p_0(T_0)$. For Mach numbers in the range $0.5 < M_1 < 1$ the recoil pressure is close to $0.55 p_0(T_0) - 0.6 p_0(T_0)$. Calculations show that for typical laser interaction conditions with surface temperature close to or exceeding the boiling point, the Mach number of the vapor flow is larger than 0.5 and, consequently, the approximation $p_r \sim 0.55 p_0(T_0)$ is justified. It is known that the saturation vapor pressure can be presented in following form

$$p_0(T_0) = B T_0^{-1/2} \exp\left(-\frac{U}{k T_0}\right) \quad (2.22)$$

where B is an empirical constant, and $U = \frac{m_a L_v}{k N_a}$ is the latent heat of evaporation per single atom.

Finally, for the recoil pressure we have

$$p_R(T_0) = A(M_1) B T_0^{-1/2} \exp\left(-\frac{U}{k T_0}\right) \quad (2.23)$$

where $A(M_1)$ is the ambient pressure dependent (through flow Mach number, M_1 , at the end of Knudsen layer) coefficient, which in our case is close to 0.55.

2.1.4 Multiple reflection

As the crater depth increases with the number of applied pulses, the part of the beam reflected from the surface can be intercepted by the hole surface from the opposite side. The larger the ratio of depth to radius the higher the number of reflections and reabsorptions that an individual ray in the beam can experience before it leaves the drilled cavity. Obviously, these multiple reflections and consequent reabsorptions can affect the distribution of the laser beam intensity absorbed at the hole surface, and they must be taken into account.[5]

A schematic of the multiple reflection model is shown in Figure 2.2.

$$I_{ai} = I_0 \cdot \cos \alpha_i \cdot ab \cdot (\cos \alpha_i)^{0.2} \quad (2.26)$$

$$I_{Ri} = I_0 \cdot (1 - ab \cdot (\cos \alpha_i)^{0.2}) \quad (2.27)$$

$$\begin{aligned} I_{ap} &= I_{Ri} \cdot \cos \gamma_p \cdot ab \cdot (\cos \gamma_p)^{0.2} \\ &= I_0 \cdot \cos \gamma_p \cdot (1 - ab \cdot (\cos \alpha_i)^{0.2}) \cdot ab \cdot (\cos \gamma_p)^{0.2} \end{aligned} \quad (2.28)$$

$$I_{Rp} = I_0 \cdot (1 - ab \cdot (\cos \alpha_i)^{0.2}) \cdot (1 - ab \cdot (\cos \gamma_p)^{0.2}) \quad (2.29)$$

$$\begin{aligned} I_{ak} &= I_{Rp} \cdot \cos \gamma_k \cdot ab \cdot (\cos \gamma_k)^{0.2} \\ &= I_0 \cdot \cos \gamma_k \cdot (1 - ab \cdot (\cos \alpha_i)^{0.2}) \cdot \\ &\quad (1 - ab \cdot (\cos \gamma_p)^{0.2}) \cdot ab \cdot (\cos \gamma_k)^{0.2} \end{aligned} \quad (2.30)$$

Through (2.26)~(2.30), we obtain the first absorption I_{ai} , the first reflection I_{Ri} , the second absorption I_{ap} , the second reflection I_{Rp} and the third absorption I_{ak} .

Thus at each specific point along the curve, we obtain the special first, second and third absorptions. Addition of these three absorptions gives the incident energy for each point. Then we can calculate the corresponding temperature, drilling velocity and the new shape, which are the topics of next section.

2.2 Mathematical model

The calculations will use the following assumptions:

- 1) The liquid is incompressible;
- 2) Laser power is absorbed on the sample surface (no volumetric heat generation), pressure and viscous dissipation terms are neglected in the energy equation;
- 3) The material's thermophysical parameters are independent of temperature and are different for solid and liquid phases;
- 4) The melt layer is approximated as a thin boundary layer;
- 5) The melt flow is quasi-one-dimensional along the sample surface and the component of flow velocity normal to the sample surface is assumed to be zero;
- 6) The influence of surface tension and gravity on the melt flow are assumed to be insignificant compared to the effect of evaporation induced recoil.

Assumption 2) is justified because the depth of laser radiation absorption in a metal is much smaller than the characteristic dimension of the thermal field.

Future work can include temperature dependence of material parameters disregarding the assumption 3) introduced to simplify numerical codes. The approximation of a thin boundary layer 4) is justified by the numerical results [15] showing that typical melt thickness in the beam interaction zone is much

smaller than the beam diameter. In future work assumptions 4) and 5) can be removed and the three-dimensional flow field can be simulated. Assumption 6) is justified by the numerical results reported previously [14, 15, 17].

Taking into account the assumptions 1) - 3), the equations of conservation of mass, momentum and energy can be written in following form:

$$\operatorname{div} \vec{v} = 0 \quad (2.31)$$

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \operatorname{grad} \vec{v} \right) = -\operatorname{grad} p + \mu \Delta \vec{v} \quad (2.32)$$

$$\frac{\partial T}{\partial t} + \vec{v} \operatorname{grad} T = \frac{k}{c\rho} \nabla^2 T \quad (2.33)$$

where v , ρ , c , T , and k are the velocity, density, specific heat, temperature and heat conductivity of solid or liquid material, μ is the melt viscosity, and p is the pressure.

A mixed-type boundary condition is applied on the liquid - vapor boundary

$$-k \frac{\partial T}{\partial z} \Big|_{\text{surf}} + \rho V_{\text{dv}} L_v = (1-R) I_{\text{laser}} \quad (2.34)$$

where k is the heat conductivity of solid or liquid phase, $\frac{\partial T}{\partial z} \Big|_{\text{surf}}$ is the temperature gradient at the surface, ρ is the density of condensed phase, V_{dv} is the component of boundary velocity due to evaporation, R is the angular

dependent reflection coefficient for the laser wavelength, and I_{laser} is the intensity of the laser beam at the surface. Because for typical welding conditions the melt surface temperature is much lower than the material critical temperature, the energy of evaporation of a single atom, U , can be approximated as a constant. Then the component of boundary velocity due to evaporation V_{dv} can be expressed by equation [16]

$$V_{\text{dv}} = V_0 \exp\left(-\frac{U}{KT_{\text{surf}}}\right) \quad (2.35)$$

where V_0 is a coefficient of the order of magnitude of the velocity of sound, and T_{surf} is the local surface temperature.

The assumptions of the thin boundary layer 4) and one-dimensional character of melt flow 5) allow integration of equation (2.31) over the melt thickness, h . This gives an equation for drilling velocity, V_{d} .

$$V_{\text{d}} = -\frac{\partial(v_{\text{m}}h)}{\partial x^*} - V_{\text{dv}} = -V_{\text{dm}} - V_{\text{dv}} \quad (2.36)$$

Here v_{m} is the melt velocity along the sample surface, axis x^* is directed along the sample surface and V_{dm} is the component of drilling velocity due to melt motion. Note that the drilling velocity, V_{d} , is directed normal to the sample surface.

Application of the thin boundary layer assumption allows the pressure across the molten layer, p , to be approximated by the evaporation recoil pressure, p_{r} ,

applied to the melt surface. Using the results presented in references [7,8] one can show that the evaporation recoil pressure at the surface is related to the surface temperature, T_{surf} , according to equation

$$P_r = AB_0 T_{surf}^{\frac{1}{2}} \exp\left(-\frac{U}{kT_{surf}}\right) \quad (2.37)$$

where A is an ambient pressure dependent coefficient, and B_0 is an empirical constant.

Then the momentum equation (2.32) can be written in following form:

$$\frac{\partial v_m}{\partial t} + v_m \frac{\partial v_m}{\partial x^*} = \frac{1}{\rho} \frac{\partial p_r}{\partial x^*} - \frac{\mu}{\rho} \frac{\partial^2 v_m}{\partial z^2} \quad (2.38)$$

Taking into consideration melt motion with an average velocity v_m determined by equation (2.38) and normal to the surface motion of the melt surface with velocity V_d determined by equations (2.35,2.37,2.38), the heat transfer equations for the liquid and solid phases can be presented in the following form:

$$\frac{\partial T}{\partial t} + v_m \frac{\partial T}{\partial x^*} + V_d \frac{\partial T}{\partial z} = \frac{k_l}{\rho_l c_l} \left(\frac{\partial^2 T}{\partial x^{*2}} + \frac{\partial^2 T}{\partial z^2} \right) \quad (2.39)$$

$$\frac{\partial T}{\partial t} = \frac{k_s}{\rho_s c_s} \left(\frac{\partial^2 T}{\partial x^{*2}} + \frac{\partial^2 T}{\partial z^2} \right) \quad (2.40)$$

Here the subscripts "l" and "s" refer to the liquid and solid phases and ρ, c, T and k are the density, specific heat, temperature and heat conductivity, respectively.

The local absorbed laser beam intensity I_{abs} , required for the calculation of the thermal field, is determined from the known intensity distribution and by calculating the multiple reflection/absorption of the incident beam in the drilled crater.

2.3 Numerical method of solution

The equations presented in the section "Mathematical Model" are solved numerically using an algorithm described by the flow chart shown in Figure 2.3.

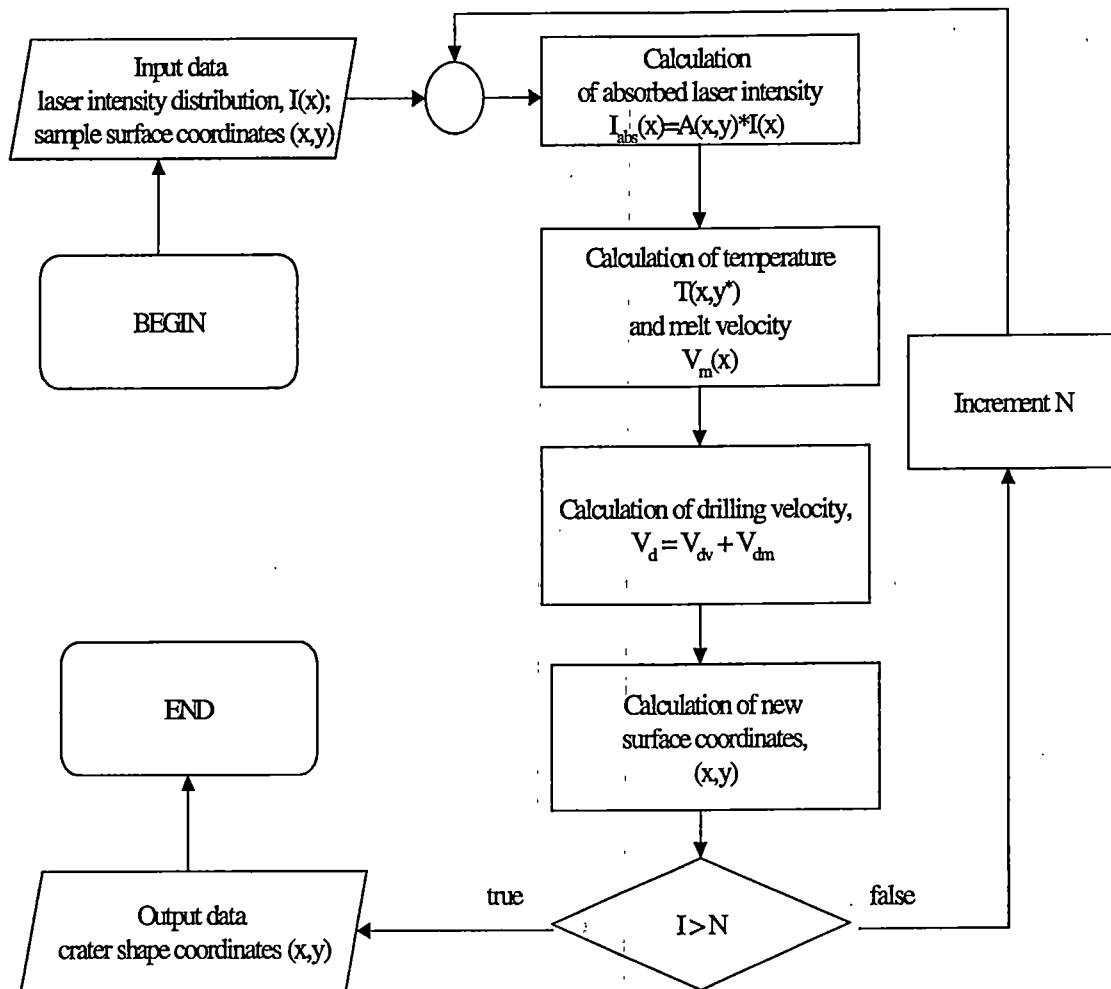


Figure 2.3. Flow chart for the calculation algorithm

A one-dimensional grid is generated along the direction (x-axis) normal to the laser beam axis with zero at the intersection of the laser beam axis and the initial sample surface. The number of nodes on the x-axis is 1000. The y-axis is assumed to coincide with the laser beam axis. The values of the laser beam intensity and the y-coordinates of the initial shape of the sample surface at the

nodes of the grid are introduced as the input data. Note that the values of y-coordinate of the sample surface are continuous, unlike x-coordinate values, which are fixed to correspond to the grid.

Next, the absorbed laser beam energy is calculated at the nodes taking into account angular dependence of the absorption coefficient and two subsequent reflections. If the reflected ray intersects the sample surface between the nodes the calculated absorbed energy is assigned to the closest intersection node.

The calculated absorbed energy is used to compute the temperature distribution along the normal to the sample surface at the nodes. Because the heat penetration depth is much smaller than the scale at which the shape of the crater changes significantly, the heat transfer is computed in a one-dimensional approximation along the normal.

An explicit difference scheme is used for the temperature calculation. The temperature $T(i,k)$ is calculated from equations (2.39, 2.40), with boundary condition (2.34). Index i is the number of a node along the x-axis, and index k is the number of a node in the direction normal to the sample surface.

$$\begin{aligned}
T(i,1) = T(i,1) + 0.5 \frac{dt}{dx^*(i)} (T(i-1,1) - T(i+1,1)) v_m(i) + \\
\frac{a dt}{dx^{*2}(i)} (2T(i,1) - T(i-1,1) - T(i+1,1)) + \\
\frac{a dt}{dz^2} (T(i,2) - T(i,1)) + \frac{dt}{c\rho dz} (I_{abs}(i) - \rho L_v V_{dv})
\end{aligned} \tag{2.41}$$

Here dt is the calculation time step, $dx^*(i)$ is the distance along the sample surface between two points on the sample surface corresponding to the associated nodes, the temperature inside the sample is calculated using the following difference scheme:

$$\begin{aligned}
T(i,k) = T(i,k) + 0.5 \frac{dt}{dx^*(i)} (T(i-1,k) - T(i+1,k)) v_m(i) + \\
\frac{a dt}{dx^2(i)} (2T(i,k) - T(i-1,k) - T(i+1,k)) + \\
\frac{a dt}{dz^2} (2T(i,k) - T(i,k-1) - T(i,k+1))
\end{aligned} \tag{2.42}$$

For the temperature calculations, the melt velocity v_m is assumed to be zero if the temperature is below the melting point. For the regions with temperature exceeding the material's melting point, the melt velocity is considered as known from the previous time step. The difference representation of equation (2.38) for the calculation of the melt flow velocity is as follows

$$v_m(i) = v_m(i) + \frac{dt}{2dx^*(i)} \left(\frac{p_r(i+1) - p_r(i-1)}{\rho} - v_m(i)(v_m(i+1) - v_m(i-1)) \right) - \frac{\mu}{\rho} \frac{v_m(i)}{h^2} \tag{2.43}$$

where h is the melt thickness at the point corresponding to the i -th node.

The drilling velocity is computed using the difference representation of equation (2.36)

$$V_d(i) = -\frac{(v(i+1) - v(i-1))h}{2dx(i)} - V_{dv}(i) \quad (2.44)$$

Then new coordinates of the i -th point on the sample surface are calculated:

$$\begin{aligned} nx(i) &= x(i) + V_d(i) \cos(\alpha) \\ ny(i) &= y(i) + V_d(i) \sin(\alpha) \end{aligned} \quad (2.45)$$

where α is the angle between the normal to the surface and the laser beam axis.

Finally the y coordinates of the sample surface are recalculated for the nodes on the x -axis providing the sample surface shape (drilled crater profile).

Chapter 3

Simulation Results

In order to simulate the laser drilling successfully, we have to select stable and applicable parameters to use in the computer simulation. In this chapter, we will decide how many reflections of the laser beam should be considered to get a satisfactory result, what time step and grid spacing is appropriate, what is the effect of different laser beam radial profiles, what is the effect of the incidence angle on the drilling shape, what is the temporal distribution of temperature during the laser pulse and what is the effect of melting flow on the drilling shape. Once these parameters have been determined, a simulation will be performed for direct comparison with an actual drilling experiment performed by the General Electric Corporation. [5]

3.1 Selection of parameters

3.1.1 Multiple reflections

Simulations were performed to determine the effect of one, two and three reflections.

From Figure 3.1 and Figure 3.2, we see that we get much deeper drilling with additional reflections. It is an expected result because there is still substantial energy left after the first absorption. We also see that there is not much difference between two reflections and three reflections. That is

because after the second absorption most of the energy in the beam has been absorbed. It is also important to note that the second and third reflections cause a lateral displacement of the drilled hole for non-normal incidence angles. So we conclude that it will be adequate to consider only three reflections in the following simulations.

3.1.2 Beam profiles

Simulations were performed using both top-hat and Gaussian laser beam profiles to determine the effect of beam profiles on the resulting drilling hole shapes.

Here we simulate the laser intensity in two ways. One is the gaussian shape, another is the top-hat shape. Both the Gaussian beam and the top-hat beam have the same peak intensity and beam radius. The total beam energy is not the same, the top-hat beam contains more energy than the Gaussian beam.

In Figure 3.3, we see that the Gaussian shape drills wider but shallower and the top-hat shape drills narrower but deeper. So it is apparent that the intensity distribution has a great effect on the drilling hole shape. If we just reduce the intensity, but keep the same intensity distribution pattern, we will get the same drilling shape although the depth will be shallower.

The Gaussian beam result best matches the experiment and hence, we will use a Gaussian beam profile in the remaining calculations.

3.1.3 Angle of incidence

Simulations were performed to compare the different results using 0 degree and 60 degree laser beam incidence angles.

If the laser hits the target at 0 degrees, we obtain a symmetrical drilling hole, just as shown in Figure 3.4. In practice, the incidence angle is often not normal to the work piece surface. Here we will use an angle of 60 degrees, and find (Figure 3.5) that the drilling hole is displaced from the laser beam axis. The slope in the left side is much steeper than in the right side, hence the drilled hole is not symmetric with respect to the laser beam axis. This is caused by the multiple reflections; most of second and third reflections are absorbed by the right side as shown in Figure 3.2. So the left side receives less energy, and the slope is much steeper.

In the General Electrical Corporation experiment, a 60 degree incidence angle was used.

3.1.4 Pulse duration

Simulations were performed using different laser pulse duration times (50ns, 100 ns, 150ns) to calculate the temporal temperature distribution during the pulse.

In all 3 cases, the temperature at the center point reaches steady values of approximately 5400 K after 10 ns (Figure 3.6, Figure 3.7, Figure 3.8).

Hence, we can assume that the metal temperature is steady during the whole laser pulse. We will use 100 ns for the calculation.

When we compare the drill hole shapes for these 3 cases, we find that the drilling depth scales nearly linear with the duration time (Figure 3.9). This occurs as a result of the steady temperature.

The center point evaporation during the whole laser pulse is shown in Figure 3.10. When the temperature reaches a steady value, the evaporation also reaches a steady state. The Anisimov article [2] also supports this conclusion.

The center point drilling depth during the whole laser pulse is shown in Figure 3.11. It, too, is nearly linear with time, and is also in agreement with Anisimov's conclusion.[2]

3.1.5 Time step and grid spacing

Simulations were performed using different time steps and grid spacing to determine the best time step and grid spacing to use for the General Electric comparison.

Because of the numerical stability constraint (using an explicit difference method, the heat diffusion coefficient times the time step divided by the square of the grid spacing must be less than 0.5), we have to consider the time step and the grid spacing simultaneously.

Big time steps and grid spacing would reduce the calculation time dramatically, but they are often not convergent. So we will search for the largest possible time step and grid spacing that leads to a satisfactory convergence of the numerical solution.

We tried 3 different cases: 1) time step = $2\text{e-}9$ s, grid spacing = $2\text{e-}5$ cm. 2) time step = $5\text{e-}10$ s, grid spacing = $1\text{e-}5$ cm. 3) time step = $2\text{e-}11$ s, grid spacing = $2\text{e-}6$ cm. Figure 3.12 shows that after just 200 laser pulses, the temperature of case 1 and case 2 shows strong fluctuation, but case 3 is still very smooth. This shows that case 1 and case 2 are unstable and we will use case 3. Case 3 is the best for our present computer (sparc5 workstation). If a

faster machine were used, the time step and grid spacing could be made smaller to obtain a more accurate result.

3.1.6 Melting

Simulations were attempted to evaluate the effect of the flow of molten metal.

When we account for the movement of melting metal (Figure.3.13), we find that after 200 laser pulses, the drilling hole shows a small difference. For a long drilling time, the melting effect may become important, but our present program is not stable for long time calculations that include melt flow.

Therefore, we could not confirm what the drilling difference will be after a long drilling time. The numerical method should be improved in future work to allow for the effect of melting.

In the experimental comparison, the melting effect will be neglected.

3.2 Drilling simulation results

We will simulate an actual laser drilling experiment performed at the General Electrical Corporation (GE), and will use the experimental parameters for the simulation. The drilling material is steel, the laser is CO_2 , laser peak intensity is $10^8 W/cm^2$, the incidence angle is 60 degrees, the laser beam

radius is $2 \cdot 10^{-2} \text{ cm}$. We are not sure what is the GE experimental laser duration or the total number of pulses used, but it does not affect the drilling shape much. We will select 100 ns, and we use the Gaussian beam as the beam profile.

We calculate the drill hole shapes for 1000, 2000, 3000, 4000 and 5000 laser pulses for both 0 degree and 60 degree incidence angles (Figure 3.14 and Figure 3.15). We see that the total drilling depth is nearly the same, but the drilling hole shape is very different. As discussed above, it is the result of the incidence angle and multi-reflection.

Figure 3.16 is the experimental result from the General Electric Corporation. We see that the calculated drill hole is nearly the same as the experiment after 12000 pulses. In the right side, there is some melting deposition in the experimental result. In our program, we assume the metal is either evaporated or driven away by the melting. But in reality, some melting flow will not be driven away by gas flow and will stay on the outside of the drilling hole, and some evaporation will condense and drop to the outside of the drilling hole. In our program, we assume the thickness of metal is infinity, but in reality it is limited, and it is often very thin. When the laser beam drills through the metal, the center portion of the laser beam will just pass through the hole without absorption and reflection. But in our program

we always get some reflection from this section. We can see the left side slope is shallower than the right side. It confirms our theory that multi-reflection and reabsorption are important in the determination of drilling hole shape. As a whole, the simulation satisfactorily predicts the drilling hole shape, although the pulse duration and number of pulses is unknown. This simulation method should be useful for predicting the shape of laser drilled holes in a variety of industrial applications.

Chapter 4

Conclusions and Recommendations

In Chapter 3, we calculated several different cases to determine suitable simulation parameters. Then we used these parameters to simulate one experimental result of laser drilling performed by the General Electrical Corporation. The simulation satisfactorily predicted the experimental hole shape. From this study we draw the following conclusions:

1. Beam intensity distribution has a significant effect on the crater shape within the assumption of constant peak intensity.
2. Multiple reflection and re-absorption must be taken into consideration in the 2D or 3D modeling of the hole profile. However, the heat transfer and interface propagation can be modeled using a 1D approximation under typical processing conditions.
3. The axis of the hole, drilled with a large incidence angle, deviates significantly from the laser beam axis because of multi-reflection and reabsorption.

4. Comparison with the General Electric experimental result shows that the drilled profiles can be successfully simulated using the developed computer code.

When we compare the results for melting code and no-melting code, we find that after considering the melting, the drilling hole is deeper even after just 200 laser pulses. When laser intensity is not very high or the laser pulse duration time is long, the melting flow will have an even larger effect on the drilling shape. So, for future calculations, we recommend that the melting movement effect be included.

In our present program, we use a simple explicit difference method, which determines the limitation in time step and grid spacing. We strongly recommend a change to an implicit difference method, which will be stable for large time steps and grid spacing.

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FIGURES

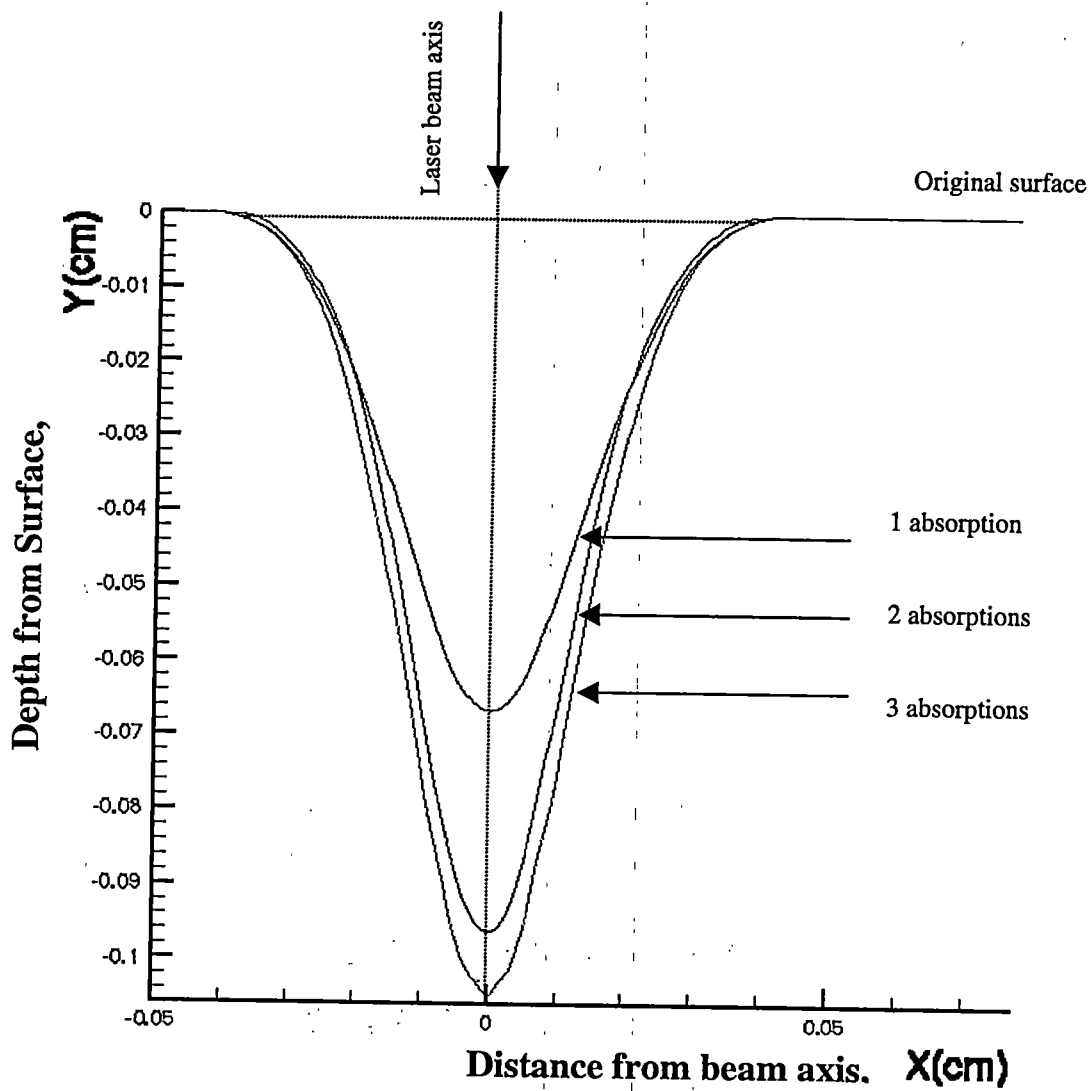


Figure 3.1 Drill hole shapes after 1000 laser pulses using 1 absorption, 2 absorptions, 3 absorptions (vertical beam)

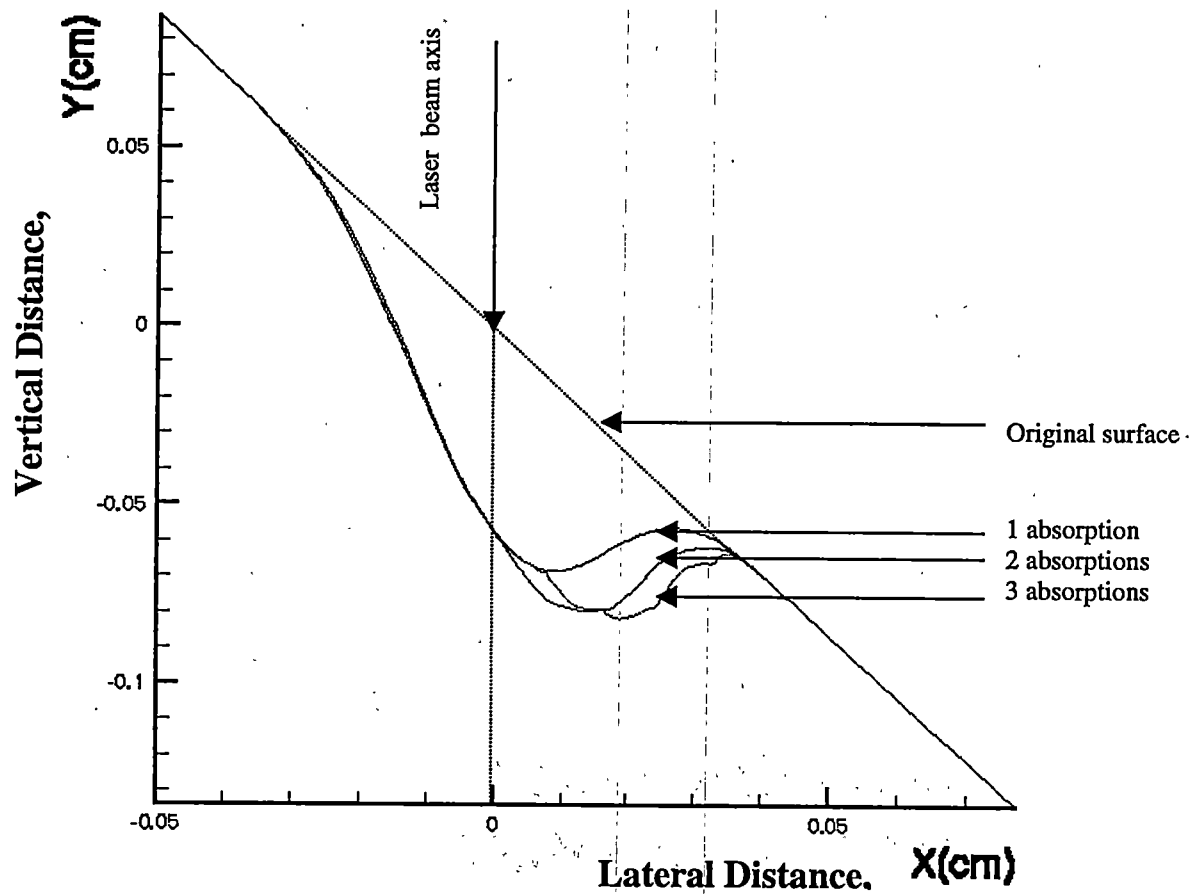


Figure 3.2 Drill hole shapes after 1000 laser pulses using 1 absorption, 2 absorptions, 3 absorptions (60 degree incidence beam)

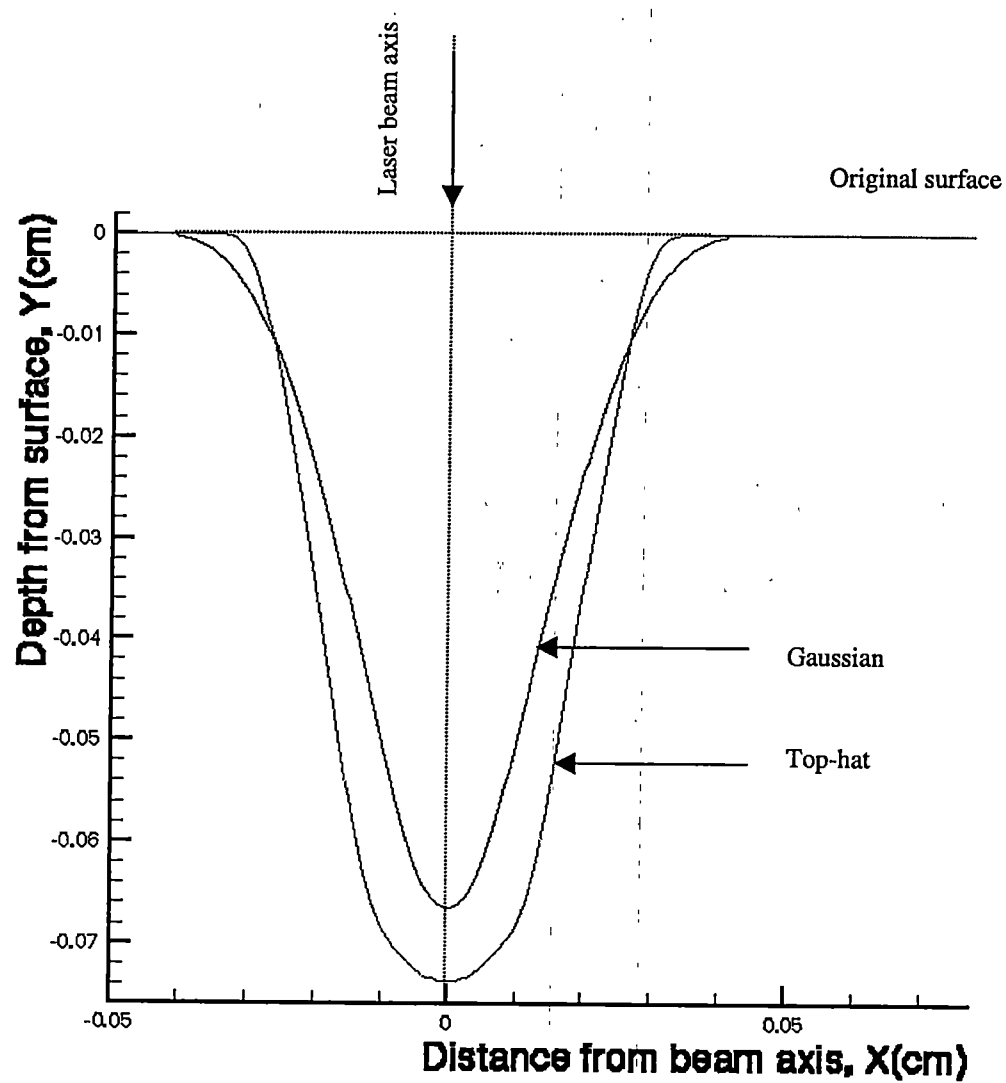


Figure 3.3 Drill hole shapes for Gaussian, top-hat laser beam (laser pulse=1000, grid=256, laser durrantion=100ns, time step=2e-2ns, grid spacing=2e-6cm)

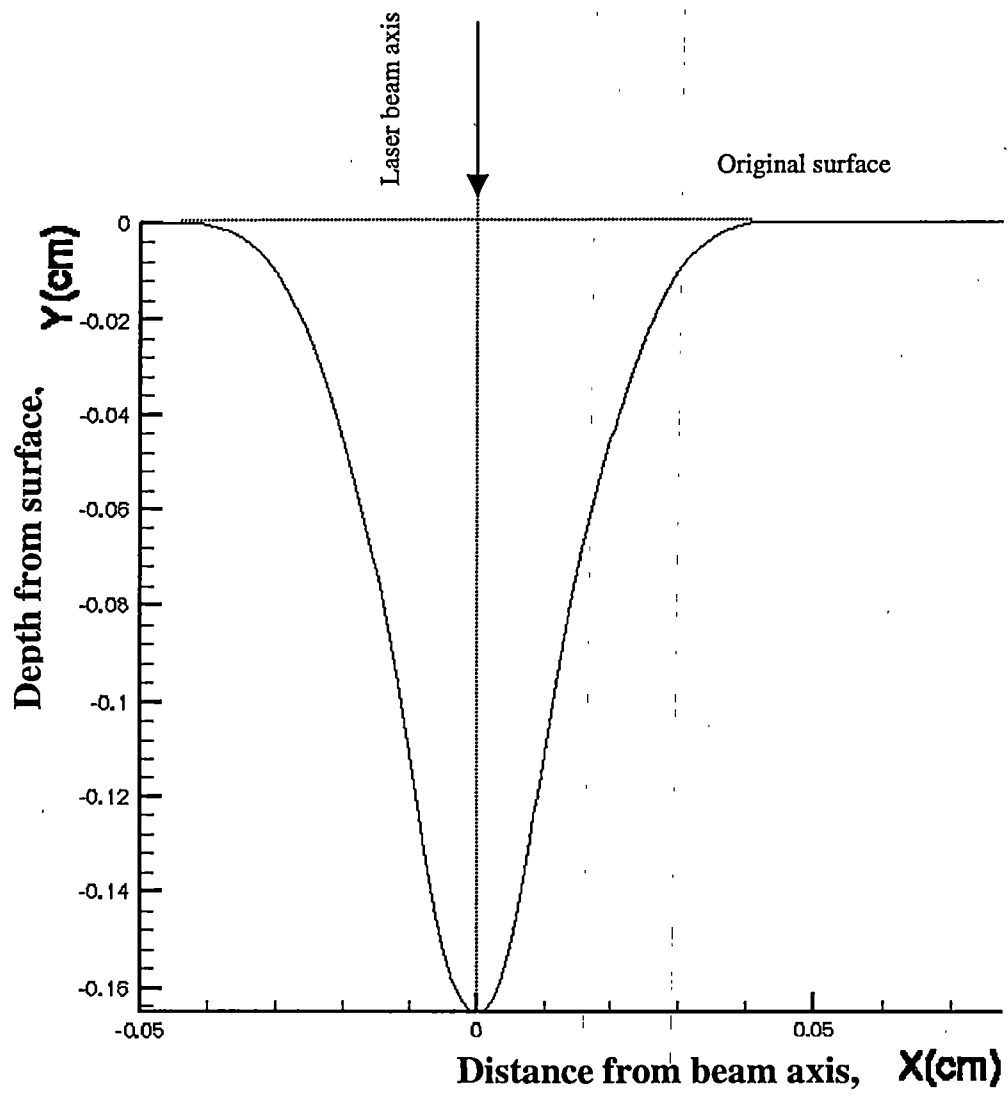


Figure 3.4 Drill hole shape for Gaussian beam after 3000 laser pulses

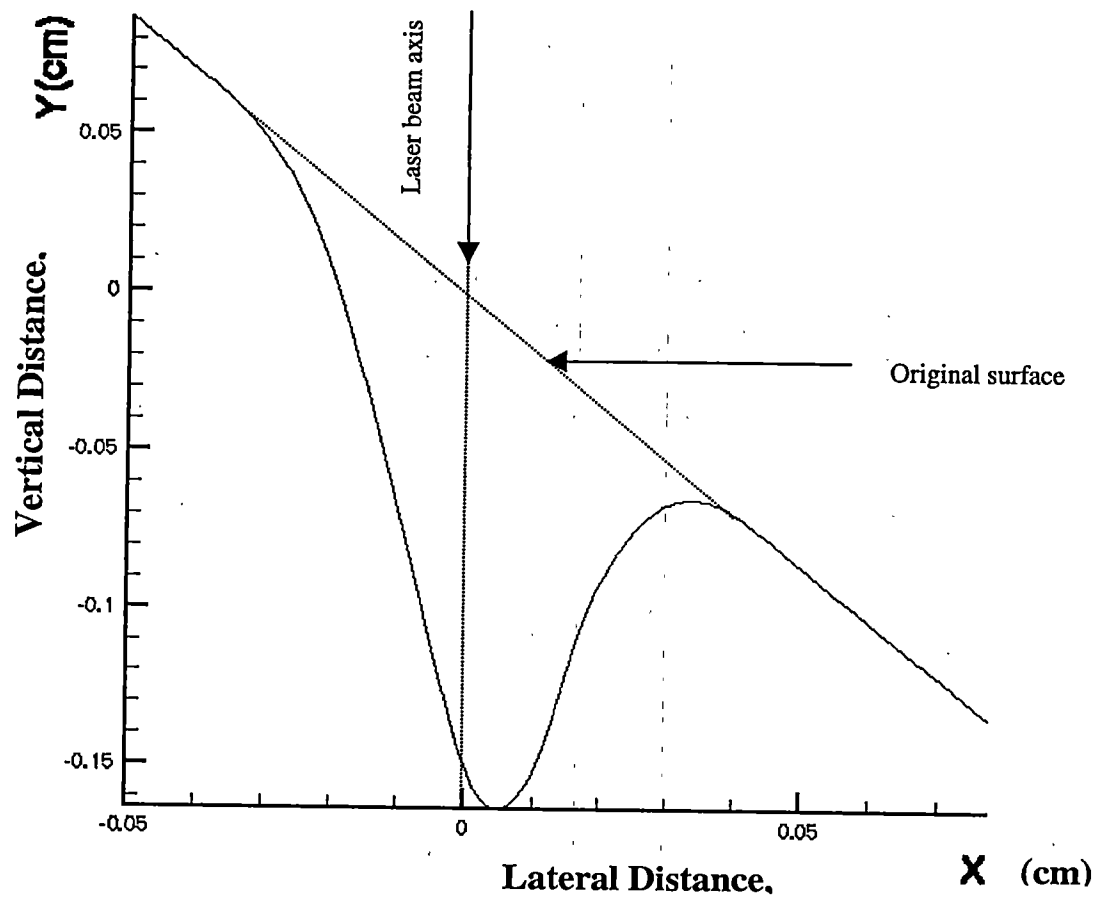


Figure 3.5 Drill hole shape for top-hat beam after 3000 laser pulses

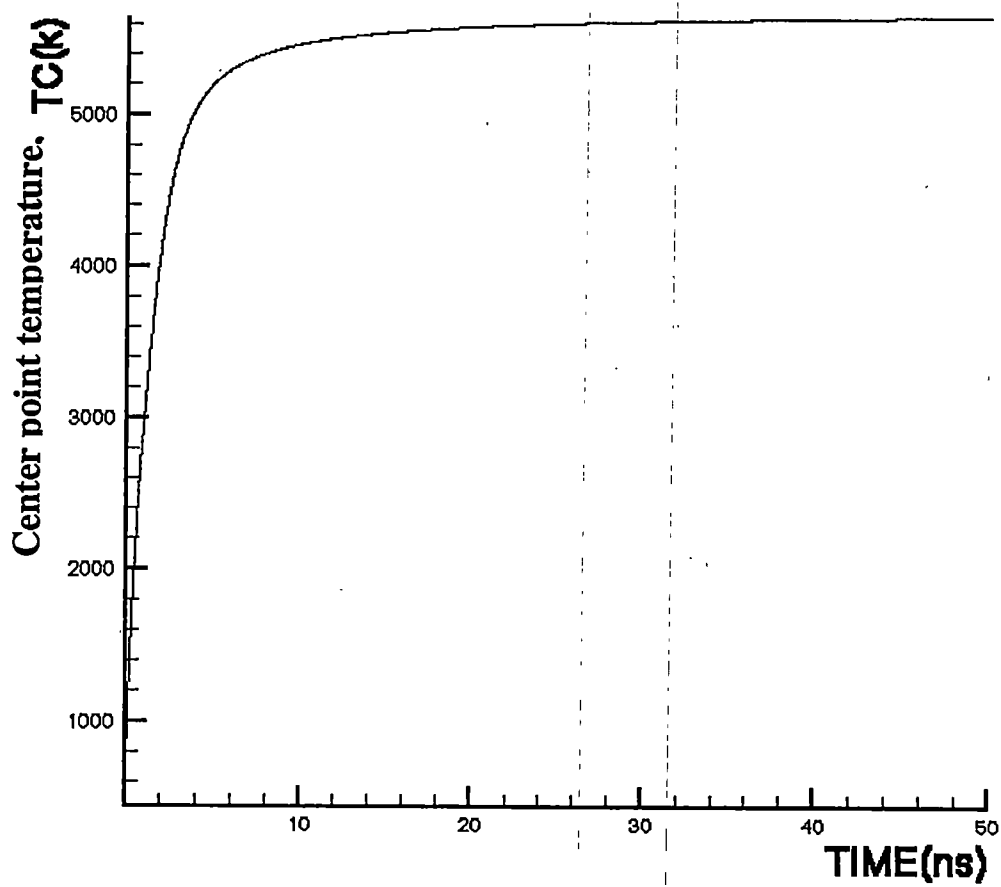


Figure 3.6 Center point temperature vs. time angle=0, laser pulse=1, grid = 256, grid spacing = $2e-6$ cm, time step = $2e-2$ ns).

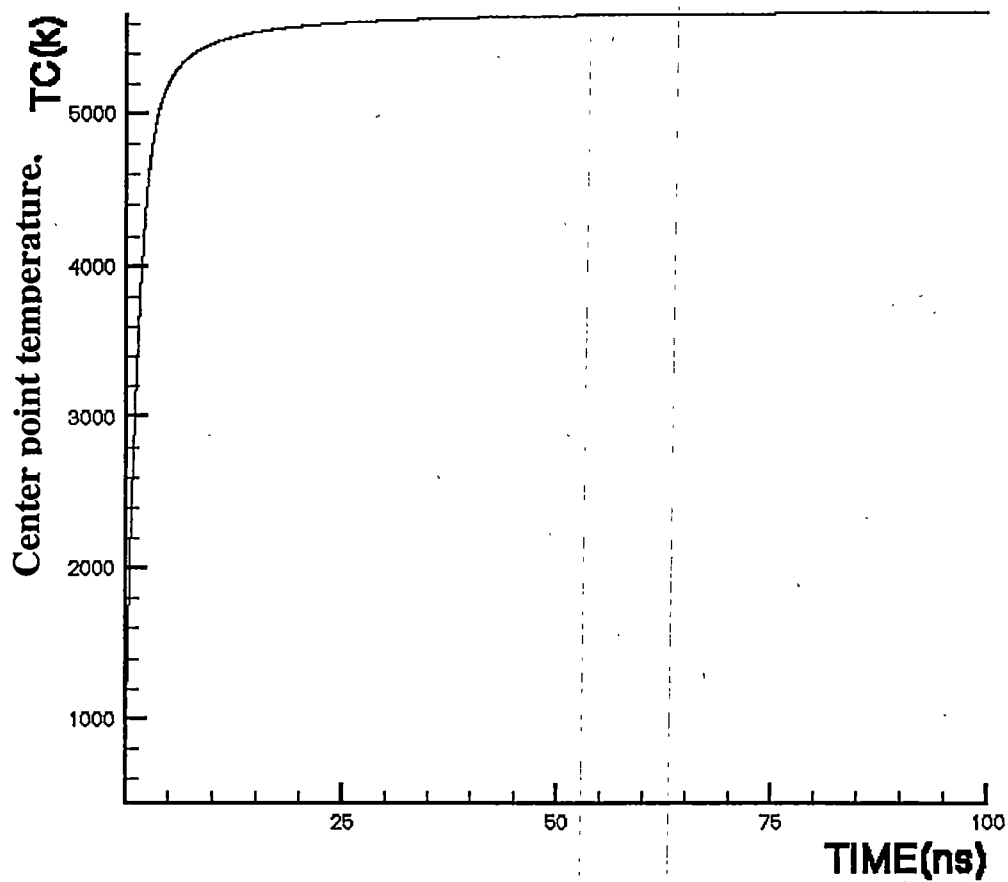


Figure 3.7 Center point temperature vs. time (angle = 0, laser pulse = 1, grid = 256, grid spacing = $2e-6$ cm, time step = $2e-2$ ns).

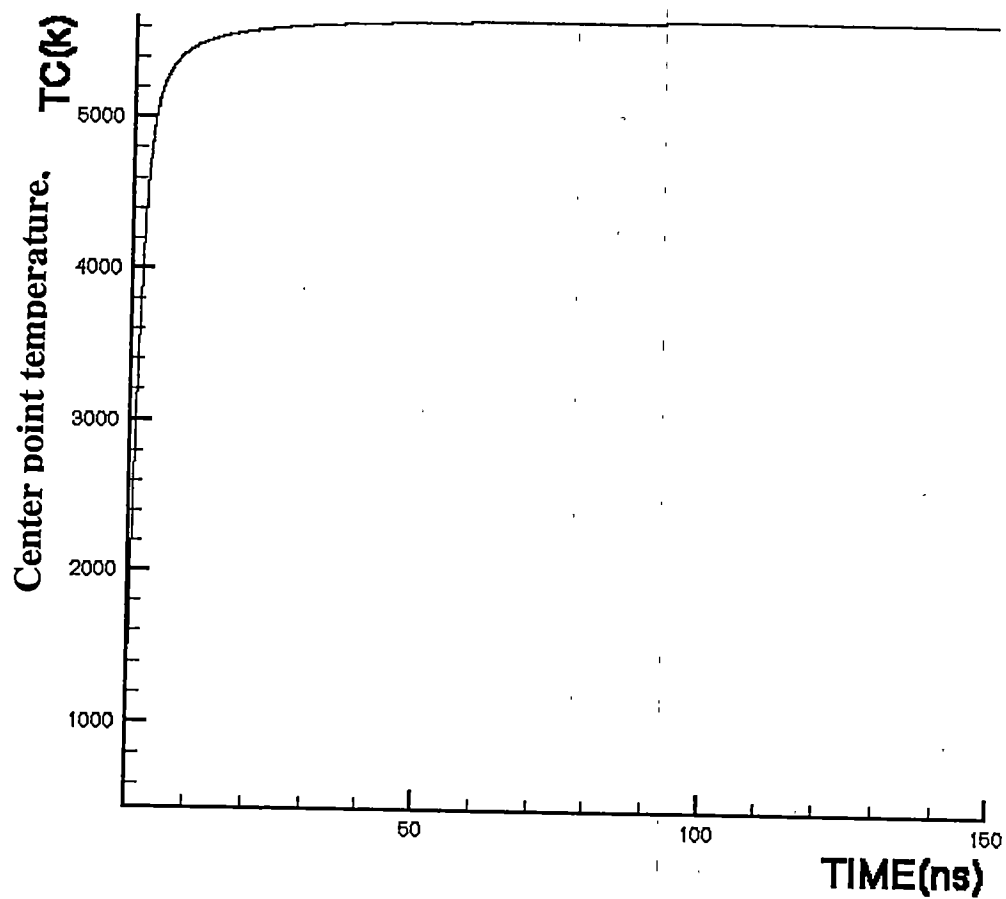


Figure 3.8 Center point temperature vs. time (angle = 0, laser pulse = 1, grid = 256, grid spacing = $2e-6$ cm, time step = $2e-2$ ns).

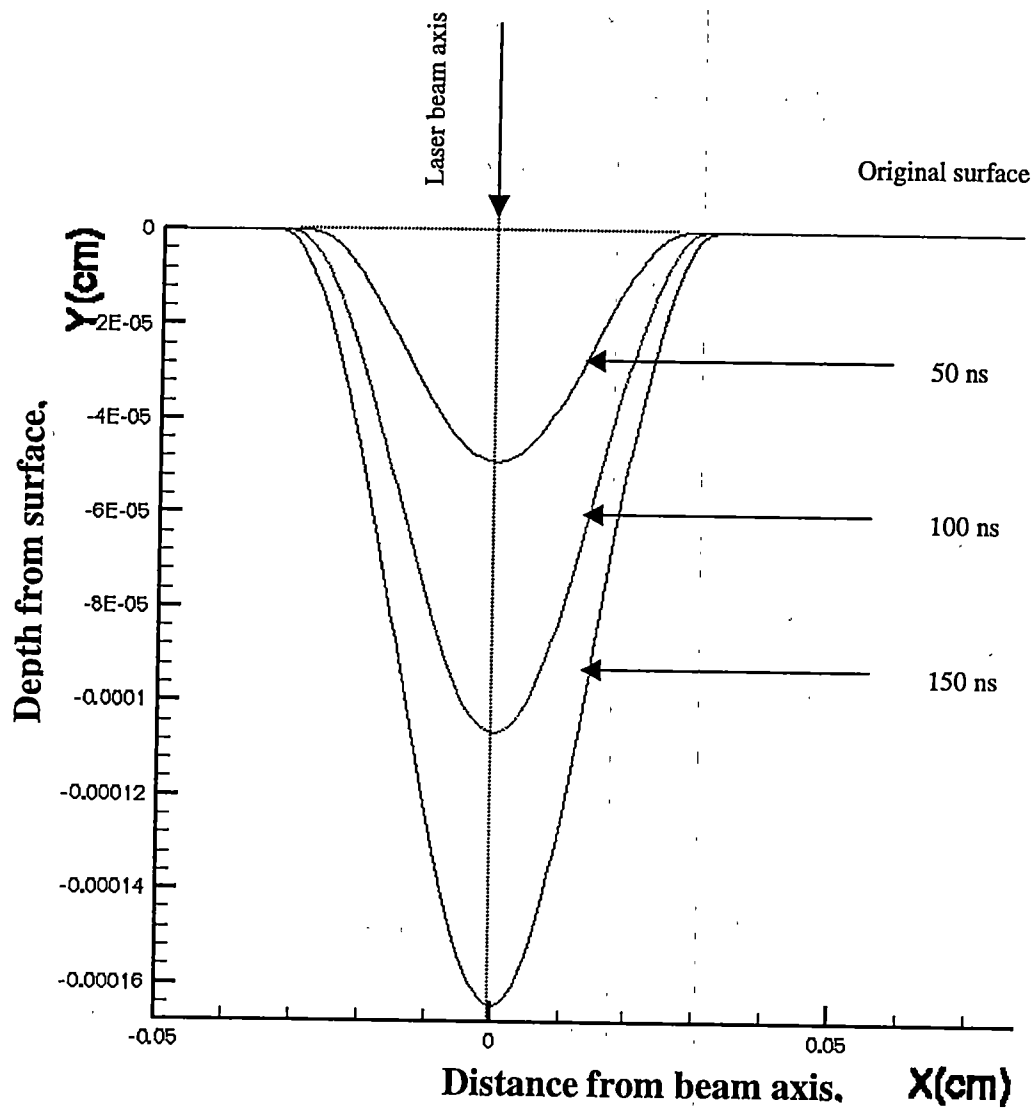


Figure 3.9 Drill hole shapes for 3 different laser pulse duration times (50, 100, 150ns)

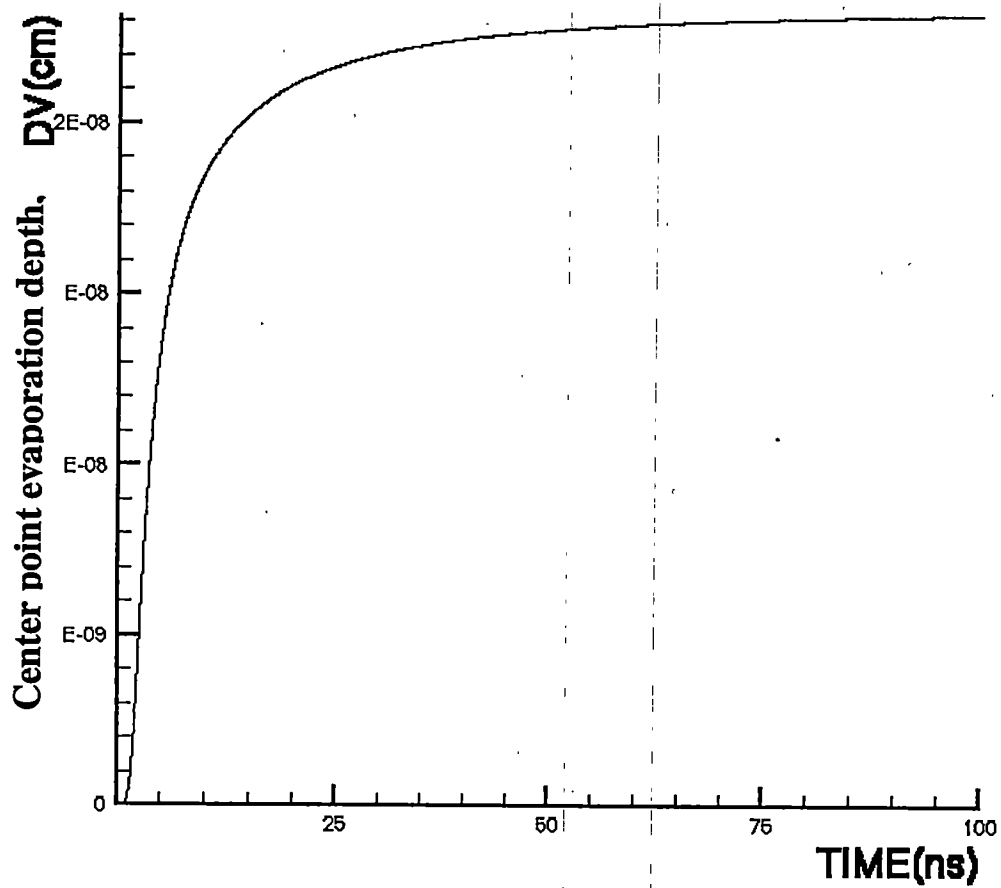


Figure 3.10 Center point evaporation vs. time (laser duration = 100ns, laser pulse = 1, grid = 256, grid spacing = $2e-6$ cm, time step = $2e-2$ ns)

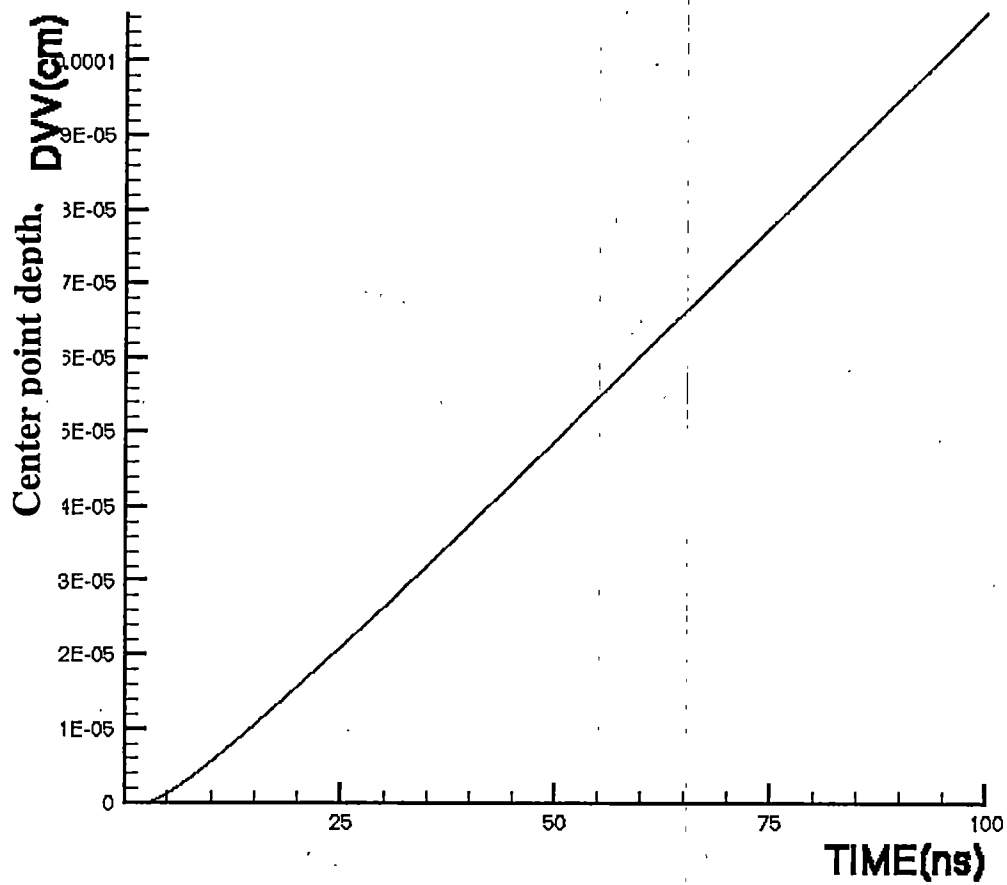


Figure 3.11 Center point depth from surface vs. time (laser duration = 100ns, grid = 256, grid spacing = $2\text{e-}6$ cm, angle = 0, laser pulse = 1, time step = $2\text{e-}2$ ns)

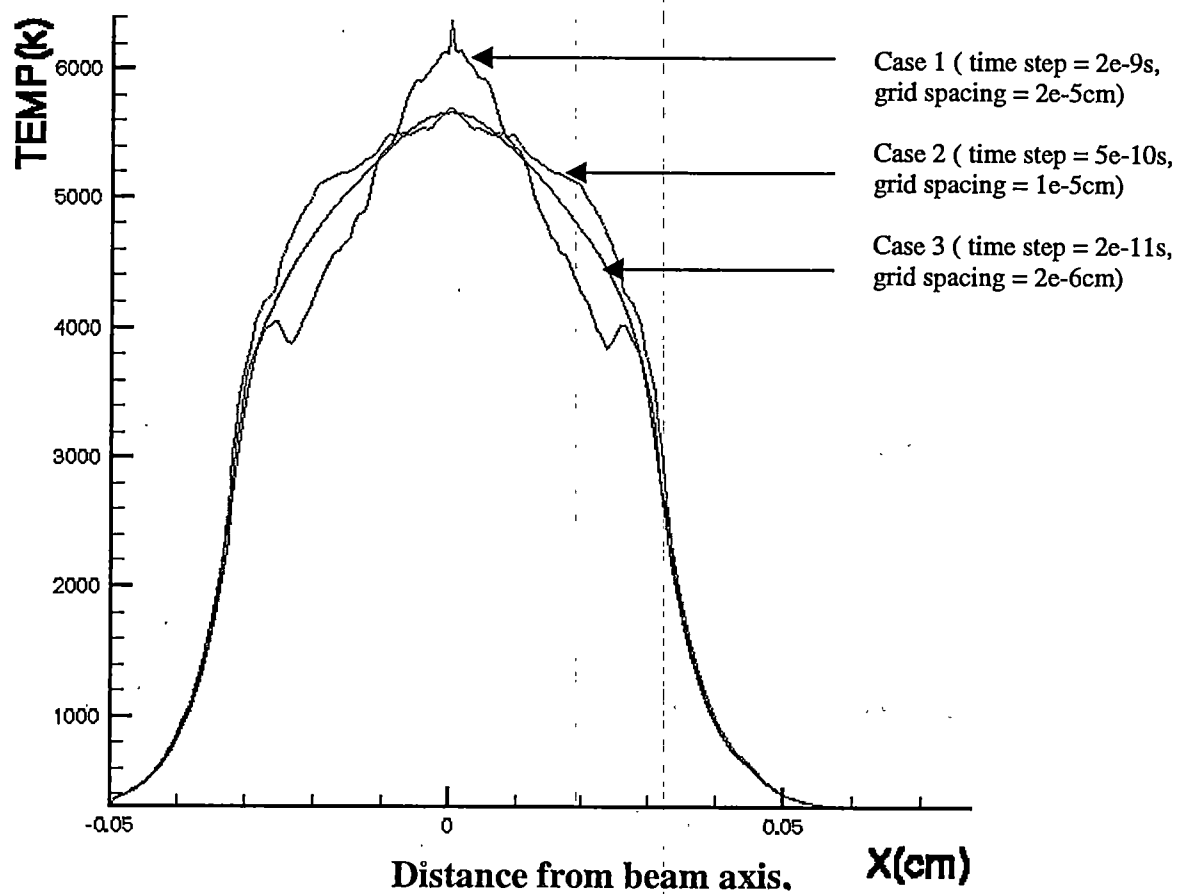


Figure 3.12 Temperature comparison for different time steps and grid spacing.

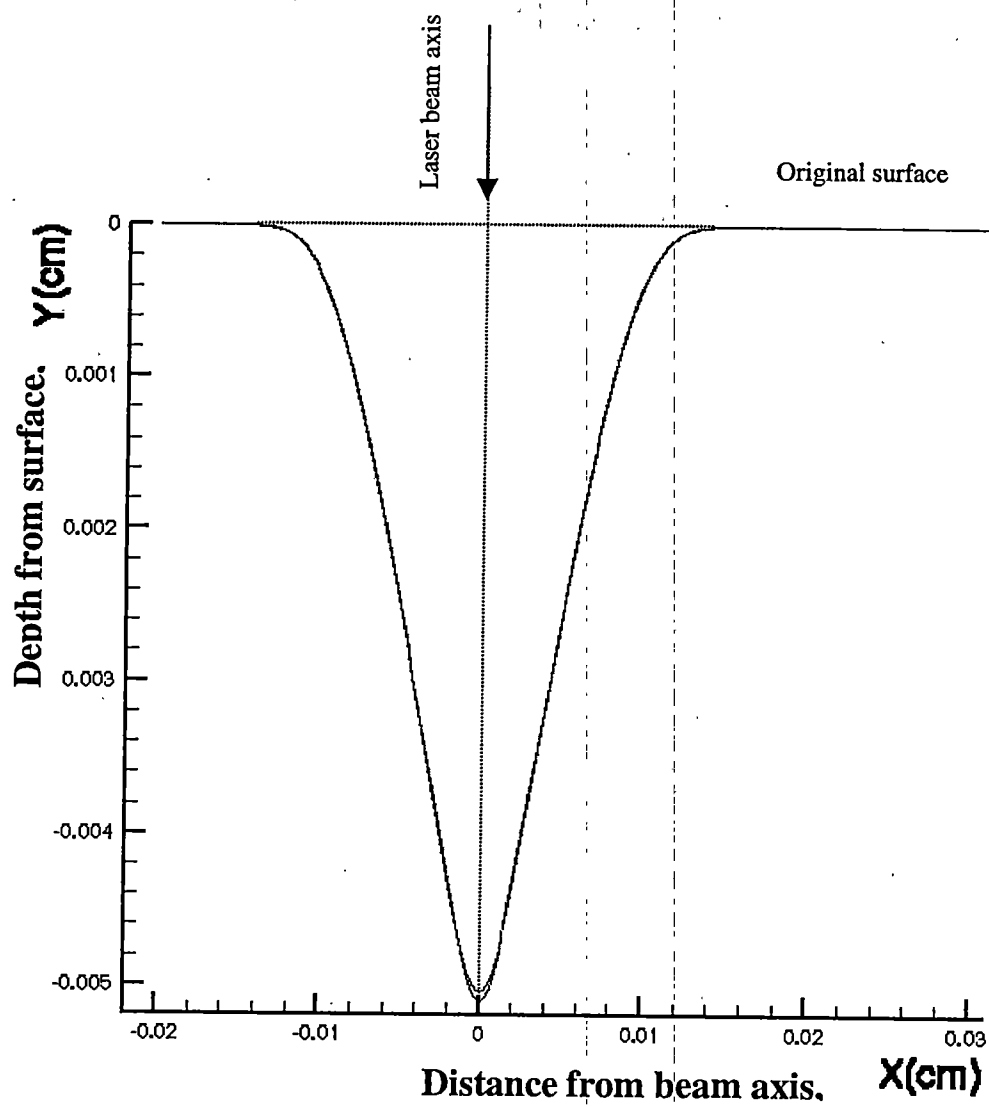


Figure 3.13 Melt vs. No-Melt (200 laser pulses, the shallower line is no-melt)

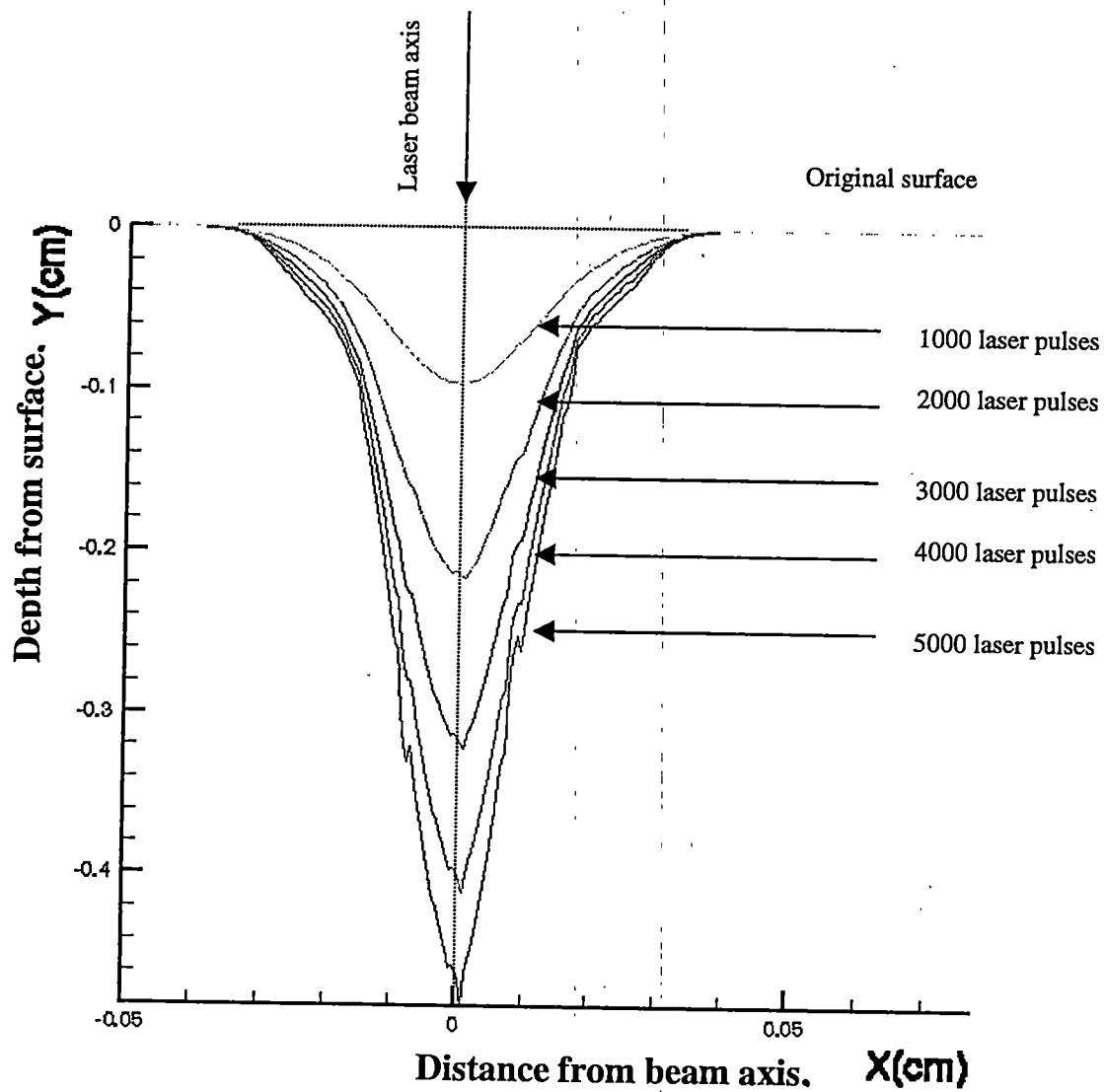


Figure 3.14 Drill hole shapes for vertical beam, 3 absorptions after 1000, 2000, 3000, 4000, 5000 laser pulses

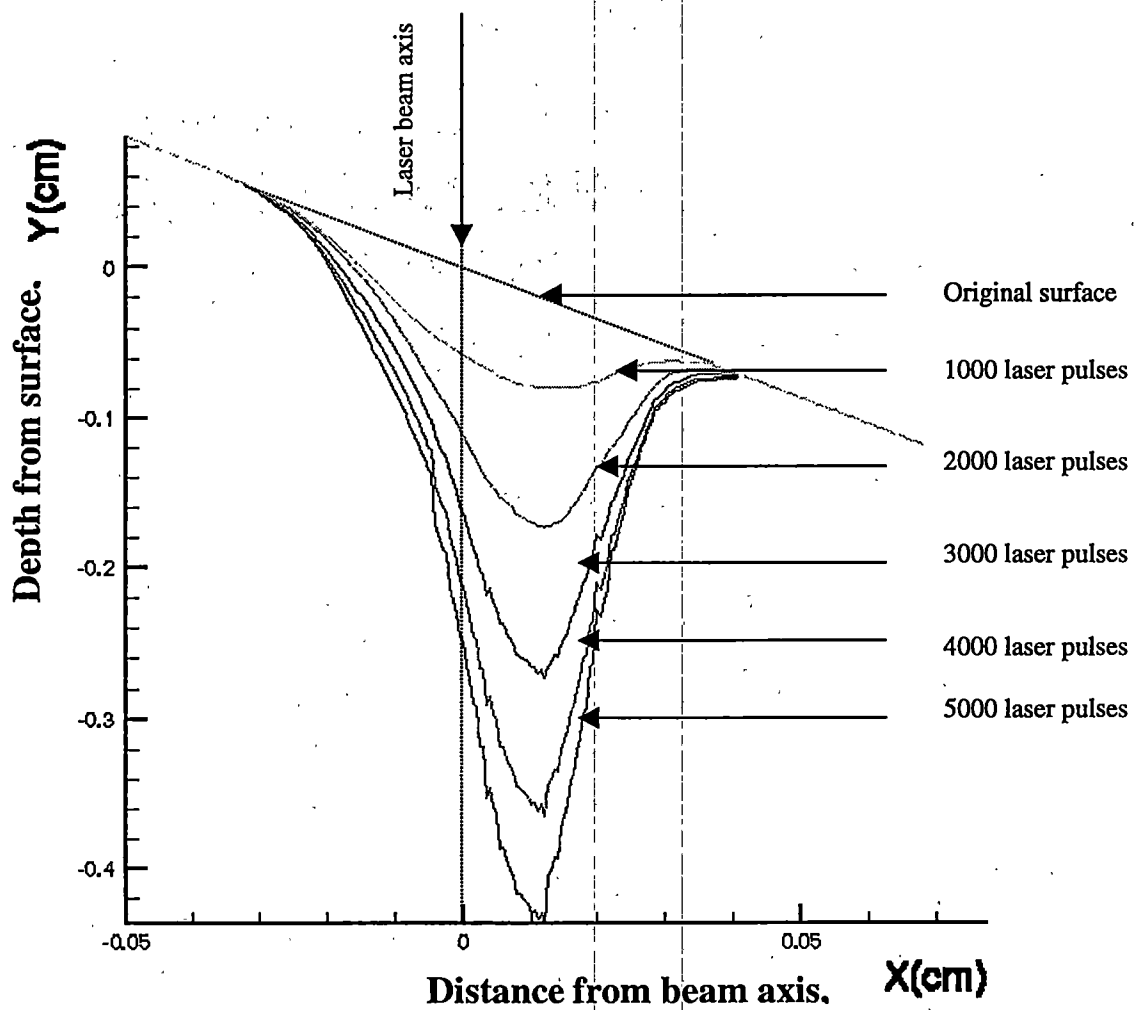


Figure 3.15 Drill hole shapes for 60 degree incidence beam, 3 absorptions after 1000, 2000, 3000, 4000, 5000 laser pulses

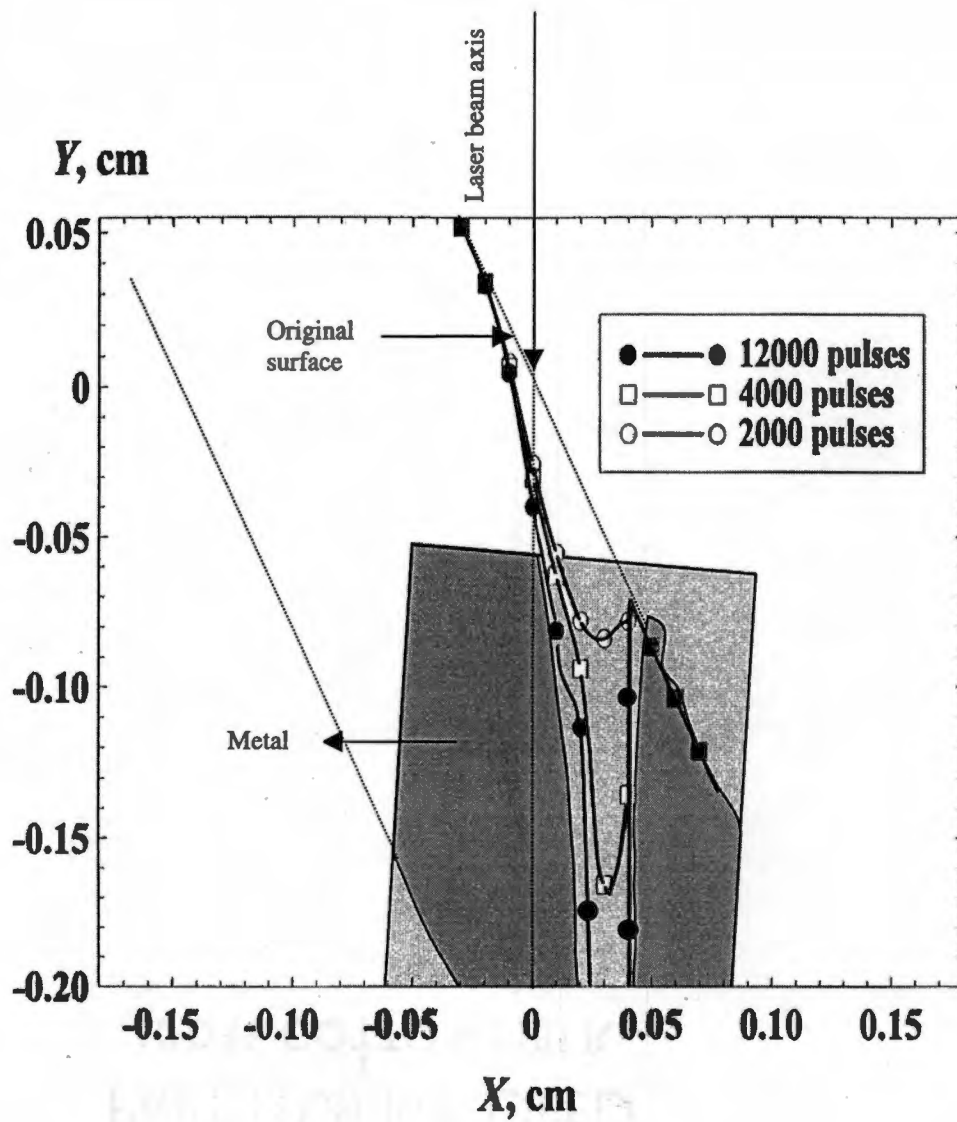


Figure 3.16 The comparison of the drilled hole profile for 60 degree incidence angle and Gaussian beam with a GE experimental result

VITA

Junlong Zhao was born in DongYang, ZheJiang Province, People's Republic of China on April 21, 1969. He graduated from DongYang Middle School in 1987. He then attended TsingHua University in Beijing where he earned his Bachelor of Science in Mechanical Engineering in 1992. After that, he worked in YangZi Electronics in ChuZhou, AnHui Province and Samsung Electronics in DongGuan, GuangDong Province. On October, 1996, he received a GRA offer from the University of Tennessee Space Institute. Since January, 1997, he attended UTSI and finished in August 1999 with a Master of Science in Mechanical Engineering.

Right now Junlong Zhao is pursuing the Ph.D. degree at the University of Tennessee Space Institute.