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THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N.Y. 10017

THEORETICAL ASPECTS OF A LASER MACHINE TOOL

G. Chryssolouris, J. Bredt, S. Kordas, and E. Wilson
Laboratory for Manufacturing and Productivity
M.I.T.
Cambridge Massachusetts

ABSTRACT

In order to overcome the limitations of traditional laser machining, a new concept of laser machining utilizing two intersecting beams is proposed. The optimization of this process requires an understanding of the phenomena involved in so-called laser "blind" cutting, as the new process and the machine performing this process are based on the production of "blind" kerfs which, by intersecting, remove a desired volume of material. This paper is a first attempt to establish a theoretical model for laser "blind" cutting, taking an energy balance approach to the problem and predicting the depth of kerfs that can be produced in a given material with a given laser power. Experimental results achieved with several ceramic materials are compared with the proposed model. Furthermore, certain issues related to the dimensional accuracy of the new process are also addressed.

INTRODUCTION

In order to overcome the limitations of traditional laser machining, particularly referring to the energy efficiency of the process and the production of three-dimensional parts, a new concept of laser machining has been proposed [1]. The new concept, utilizing two intersecting beams (Figure 1), is capable of producing parts with shapes similar to those produced by conventional tools. At the same time, the energy efficiency of the new process, in comparison with traditional laser machining, is increased by a few orders of magnitude.

This new concept is the basis for the design of a laser machine tool for the processing of advanced engineering materials such as ceramics and composites. However, application of the new concept for such purpose would be difficult if the material removal rate of the process and the dimensional accuracy and the surface quality of

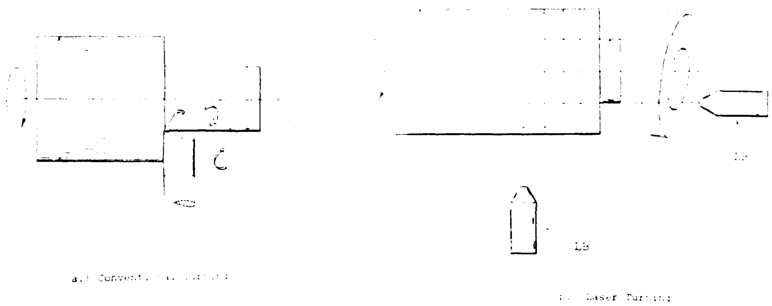


Figure 1: The Concept of Laser Turning

the produced workpieces are not acceptable. The optimization of the process with respect to the above criteria requires an understanding of the phenomena involved in laser "blind" cutting because the new process and the machine tool performing the process are based on the production of "blind" kerfs, as illustrated in Figure 2. Due to the shape of the erosion front, the material removal mechanism in "blind" cutting is more complex than in traditional "through" cutting [2]. All of the molten material must be ejected through the existing kerf. This removal process takes place on two planes almost perpendicular to one another, namely the "cutting" and "drilling" fronts. In this paper, a first attempt to establish a theoretical model for "blind" laser cutting is described, together with pertinent experimental results.

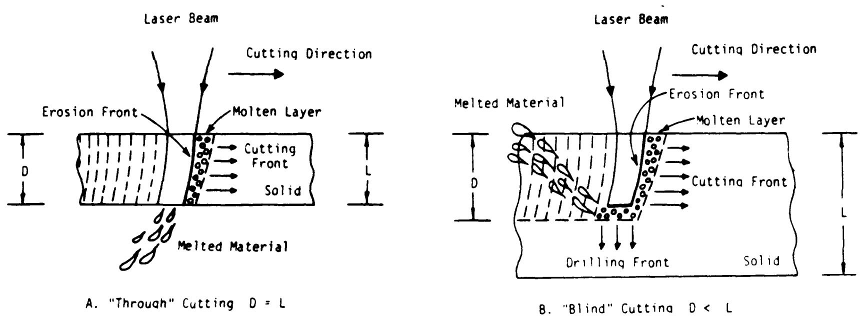


Figure 2: Material Removal Mechanism for "Through" and "Blind" Cutting

MODELLING OF LASER CUTTING

Laser cutting is one of the major applications of lasers as material removal tools. The study and modelling of the laser cutting process first requires a good understanding of the classical heat transfer problem of material heating by moving heat sources. This problem has been studied analytically by early workers [3], however, no reference to the laser beam as a heat source was given. Analysis of the moving heat source problem and the propagation of the melting front has been done by Duley [4], among others. A critical cutting speed, above which a cut is not produced, is predicted.

Several theoretical models of the laser cutting process have been published, and three different versions of laser cutting have been distinguished [6]. In laser sublimation cutting, the focussed beam heats the material to its evaporation temperature and a jet of inert gas carries the vapor out of the cutting front. In laser fusion cutting, a stronger inert gas jet is used to blow the molten material out of the kerf. The material has to be heated only above its melting point. Laser gas cutting uses a chemically active gas which reacts exothermically with the material as soon as the ignition temperature is reached. Material removal during reactive gas assisted laser cutting takes place by the ejection of molten material and by evaporation.

Schuöker, et al., [6] have analyzed the mechanism of material removal in cutting across relatively thick workpieces ("through" cutting) by considering the erosion front which occurs at a nearly vertical plane at the momentary end of the cut. It is assumed that the material is removed by ejection at the lower surface of the workpiece due to friction of the melt with the cutting gas flow and by evaporation at the erosion front.

Decker, et al., [5] roughly estimate the maximum cutting speed for a given thickness assuming high cutting speeds, narrow kerfs, and low pressure assist gas.

In [7] Bunting and Cornfield tried to establish a more general theory of thermal cutting by considering a variety of thermal cutting techniques such as lasers, electron beams, plasma jets, etc. They generalized a previously established equation for temperature distribution on a workpiece being cut by a line source by assuming a moving, diffuse heat source. This generalized equation allowed them a better correlation between experimental and theoretical results regarding cutting speed.

Copley, et al., [8] employed a continuous wave CO_2 laser to shape metallic and ceramic materials in the turning configuration by grooving and threading. Although this work deals with the formation of grooves on ceramic materials and metals, its emphasis has been more experimental, and a theoretical model of the process has not been attempted.

For modelling the proposed concept of laser turning, one must also consider the relevant work done for modelling the laser welding process, particularly that related to deep penetration welding. Although the welding process does not involve material removal through the laser action, one can use, for the modelling of the proposed process, the insight that has already been gained by various workers into the welding process related to temperature distribution due to a moving heat source. In [9] the balance between the beam power and the power dissipated by conduction, melting, and vaporization was discussed, and an approximate model for cavity formation was developed. In [10] the temperature distribution around a moving heat source was derived analytically, and the ratio of penetration depth to power required for partial penetration electron beam welding was predicted. In [11] a theoretical analysis of laser welds was performed, and a relation between laser power, transverse speed, material parameters, and efficiency of utilization of laser energy was established.

In general, research work in laser cutting, whether experimental or theoretical, assumes a given depth of cut, usually identical to the workpiece thickness, and attempts to determine a cutting speed which optimizes a particular criterion (cutting rate, surface quality, etc.). In "blind" cutting, however, the depth is not a set parameter but rather a critical variable which also has to be optimized with respect to a certain criterion.

PROCESS OPTIMIZATION

In previous publications [2, 12], it has been shown that the optimum machining conditions in laser turning could be found from geometrical considerations and from knowledge of the variation of a cutting efficiency factor η.

As a first approach to optimizing the material removal rate of the new process, a heat balance model was considered. The heat balance was used in establishing an upper bound for the material removal rate.

In order to express the deviation of the material removal process from the ideal behavior, an efficiency factor was introduced:

$$\eta = \frac{MRR_k}{MRR_{U.B.}} \qquad (1)$$

where:

MRR_k = Actual material removal rate related to the kerf

$MRR_{U.B.}$ = Theoretical upper bound removal rate also related to the kerf

In laser turning, the workpiece can be configured as shown in Figure 3. Throughout the turning operation, material is removed as rings of varying dimensions. A total material removal rate was defined as:

$$MRR_{total} = \frac{\sum_{i=1}^{q} V_i}{\sum_{i=1}^{q} t_i} \qquad (2)$$

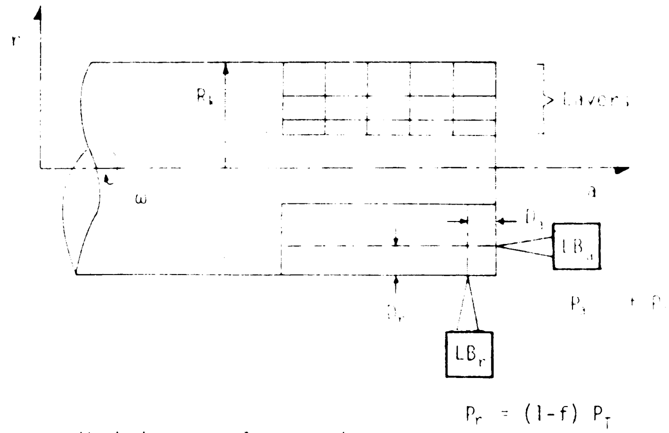
where:

MRR_{total} = Total material removal rate

V_i = Volume of ring i

t_i = Interaction time for removal of ring i

q = Number of rings required to produce final shape



ω = Workpiece angular speed
R_k = Initial radius of workpiece
LB_a = Axial laser beam
LB_r = Radial laser beam
P_T = Total Power
f = Fraction of P_T in LB_a

P_a = Power carried by LB_a
P_r = Power carried by LB_r
D_a = Axial depth of cut
D_r = Radial depth of cut

Figure 3: **Workpiece Configuration for Laser Turning--Rings with Different Dimensions**

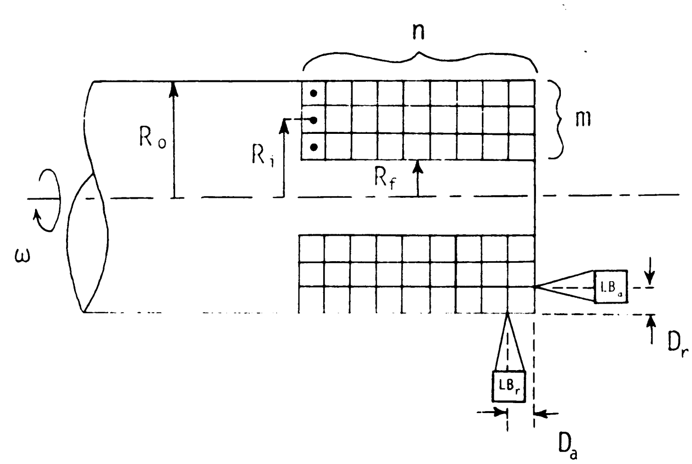


Figure 4: Workpiece Configuration for Laser Turning--Rings with Identical Dimensions

Figure 4 shows the configuration of a cylindrical workpiece where the total volume is sectioned into rings of equal dimensions. The following expression was obtained for MRR_{total}:

$$MRR_{total} = \frac{D}{d}\left[\frac{\eta P}{H}\right] \quad (3)$$

where:

MRR_{total} = Total material removal rate

D = Depth of cut

d = Laser spot size

η = Efficiency factor

P = Total laser power

In this special case (rings of equal dimensions), the optimum depth of cut was given by an expression which is independent of the workpiece dimensions:

$$D_{opt} = \frac{-\eta}{\frac{\partial \eta}{\partial D}} \quad (4)$$

where:

D_{opt} = Optimum depth of cut

The purpose of the efficiency factor η is to allow the optimization of the new process. The variation of η with depth of cut can be found from single beam experiments or from a theoretical model for "blind" cutting. Using such a model, the process parameters can be varied, and the effects of these variations on the cutting efficiency can be observed. Depth of cut predictions based on this model can also be used as a basis for further experimentation with various advanced materials.

THEORETICAL ANALYSIS OF "BLIND" LASER CUTTING

In "blind" laser cutting, the laser beam partially penetrates the moving workpiece, causing regions of the material to be vaporized, melted, or heated. The molten and vaporized masses can be blown out of the workpiece thus creating a kerf. In the experiments reported on in this paper, this removal process was achieved by directing at the laser beam focal point a high-speed gas jet created through a supersonic nozzle. The impact provided by the jet stream clears away nearly all the molten material before it resolidifies. Depending upon the speed of the workpiece and the power of the jet stream, material may be ejected either in the forward or backward directions. It is desirable that material be ejected in the forward direction to minimize the contact time of the melt with the walls of the kerf.

The geometry of the "blind" kerf is primarily determined by the dimensions of the heat-affected regions, resulting from the heat of the laser source. The shape of the heat-affected regions depends upon numerous factors, including the speed of the workpiece and the spatial profile of the laser beam. A first approximation can be made by assuming a cylindrical heat source with a uniform temperature profile. This assumption facilitates considerably the formulation of equations describing the geometric boundaries of the heat-affected regions.

Figure 5 shows schematically the different heat-affected zones created by the laser beam. It is assumed that the material is moving under the beam in the feed direction with a velocity v. Furthermore, the assumption has been made that the material under the laser spot is vaporized to a depth z, forming a cylinder of diameter d (the spot size of the laser beam) and depth z. This assumption implies that there is enough laser power density to bring this amount of material to vaporization. As the material moves under the laser beam, in the steady-state condition, the vaporized cylinder with a temperature T_k also moves with a speed v and creates a molten region around it. For a given material, the size and shape of this region depends primarily upon the speed v and the laser power. In order to determine the size of the different regions, it has been assumed that the melting front is at a distance t_f from the vaporized cylinder and that the bottom and the sides of the kerf are at a

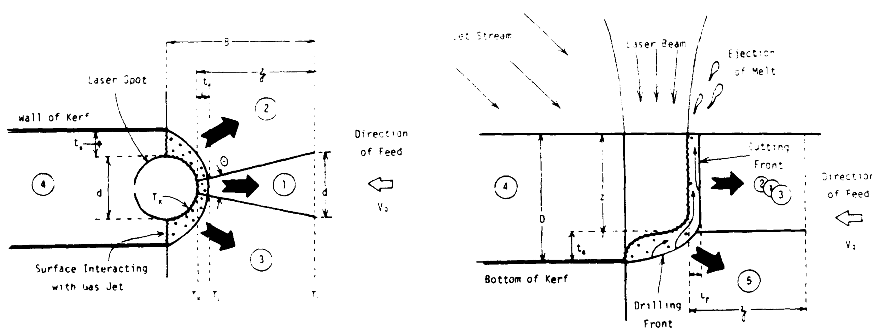


Figure 5: Regions of Material Removal During Laser "Blind" Cutting

distance t_s from the bottom and the sides of the cylinder respectively. The gas jet "follows" the laser beam, and the kerf is assumed to have straight walls. Heat is dissipated radially along the axis of penetration. Heat conducted forward is available to melt or decompose new material. A distance ζ can be defined as:

$$\zeta = \frac{\alpha}{v} \qquad (5)$$

where:

α = Thermal diffusivity

v = Surface speed

The quasi-stationary heat flow due to a moving heat source has been treated in [3] and a brief summary of this analysis related to one dimensional heat flow is as follows: The differential equation of heat flow expressed in rectangular co-ordinates (x, y, z) which are referred to a fixed origin in the solid has the well-known form:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{6}$$

where:

T = Temperature

t = Time

x, y, z = Rectangular co-ordinates

α = Thermal diffusivity

Assuming that:

- the physical characteristics of the material are constant
- the speed v and the rate of heat input q are constant
- the heat is supplied by a point source of strength q moving relative to the workpiece with a constant speed v along the x-axis
- the heat flow is quasi-stationary i.e., $\frac{\partial T}{\partial t} = 0$

one can determine the temperature distribution around the moving heat source for the linear flow of heat as:

for $\xi<0$ $$T - T_o = \frac{q''}{c\rho v} \tag{7}$$

and for $\xi>0$ $$T - T_o = \frac{q''}{c\rho v} e^{\frac{-v\xi}{\alpha}} \tag{8}$$

where:

ξ = x-vt

q'' = rate of heat per unit section

T_o = initial temperature of the solid

Equation (8) shows that $\frac{q''}{c\rho v}$ is the rise of temperature at the location of the source i.e., for $\xi = 0$. Using Equation (5) one can rewrite Equation (8) as follows:

$$T - T_o = \frac{q''}{c\rho v} e^{\frac{-\xi}{\zeta}} \tag{9}$$

For $\xi = \zeta$ the Equation (9) becomes

$$T - T_o = \frac{q''}{c\rho v} \cdot \frac{1}{e} \tag{10}$$

Equation (10) shows that ζ determines the distance between the heat source and a point along the axis x which has a temperature rise $\frac{1}{e} \times \frac{q''}{c\rho v}$. Since ζ has been defined as $\frac{\alpha}{v}$ one can conclude that for a given material with a constant diffusivity α the distance ζ decreases proportional to the speed v.

The distance ζ and the spot size d of the laser beam determine the size of Region 1 since the angle Θ can be calculated as:

$$\frac{\Theta}{2} = \tan^{-1} \frac{d}{2B} \qquad (11)$$

where:

Θ = Vertex angle of Region 1

d = Laser spot size

$B = \zeta + d/2$

At higher speeds v, the distance ζ decreases, and, consequently the angle Θ increases. However, for the range of speeds used in the present investigation and for ceramic materials, the angle Θ remains practically constant at the approximate value of 90°. The angle Θ defines all four regions where heat is dissipated radially, namely: Region 1 for forward conduction, Regions 2 and 3 for side conduction, and Region 4 for backward conduction. Region 5 accounts for the areas beneath the laser spot. The thickness of the erosion front in the forward direction, t_f, can be determined by considering heat balance between the laser spot (cylindrical heat source) and the melting isotherm T_i. Assuming steady-state conditions and constant conductivity k, one can derive the following equation:

$$\rho(C_p \quad (T_i \quad - T_o) + L)\ v \quad = k\left(\frac{T_k - T_i}{t_f}\right) \qquad (12)$$

where:

C_p = Specific heat

T_i = Melting point

T_o = Ambient temperature

T_k = Temperature at the laser spot

ρ = Density

L = Latent heat

t_f = Forward erosion front thickness

k = Thermal conductivity

From (12), the following expression for t_f is obtained:

$$t_f = \frac{\alpha}{v} \left[\frac{T_k - T_i}{(T_i - T_o) + (L/C_p)}\right] \qquad (13)$$

The thickness of the erosion (cutting) front at the sides and the thickness of the drilling front at the bottom of the laser spot, t_s, is estimated by considering another heat balance for Regions 2, 3, and 5:

$$v\ t_s\ Z\ \rho\left[L + \left(\frac{T_k + T_i}{2}\right) C_p\right] = k \cdot A_s \left(\frac{T_k - T_i}{t_s}\right) \qquad (14)$$

where:

t_s = Side erosion front thickness

z = Laser beam penetration

$\frac{T_k + T_i}{2}$ = Average temperature between laser spot and melting isotherm

$$A_s = (\pi - \Theta)\ \frac{zd}{2} + \frac{\pi d^2}{4} \qquad (15)$$

From (14), the following approximate expression for t_s is obtained:

$$t_s = \sqrt{\frac{\alpha(\pi-\Theta)d}{2v}\left(\frac{T_k - T_i}{(T_k + T_i)/2 + L/C_p}\right)} \qquad (16)$$

The parameters t_f and t_s are used to calculate the heat flux to the front, side, and bottom of the laser spot:

$$\dot{Q}_f = k \cdot A_f \left(\frac{T_k - T_i}{t_f}\right) \qquad (17)$$

and

$$\dot{Q}_s = k \cdot A_s \left(\frac{T_k - T_i}{t_s}\right) \qquad (18)$$

where:

$\dot{Q}_f$ = Forward heat flux

$\dot{Q}_s$ = Side and bottom heat flux

$A_f = \frac{\Theta dz}{2}$

The sum of the values for $\dot{Q}_f$ and $\dot{Q}_s$ is the rate of heat flux. This amount of heat must be supplied by the laser, assuming no further losses occur. Thus, the following equation can be written:

$$P = \dot{Q}_f + \dot{Q}_s \qquad (19)$$

P = Average laser power

The above equation can be solved for z:

$$z = \frac{P - \frac{\pi}{4} d^2\ k\left[\frac{T_k - T_i}{t_s}\right]}{k\frac{\Theta}{2}d\left[\frac{T_k - T_i}{t_f}\right] + k\left(\frac{\pi-\Theta}{2}\right) d \left(\frac{T_k - T_i}{t_s}\right)} \qquad (20)$$

The depth of a single-pass "blind" cut is then given by:

$$D = z + t_s \tag{21}$$

The depth of cut, D, is normalized with respect to laser spot size and is compared with experimental data as a function of normalized energy density.

EXPERIMENTAL RESULTS

In order to calculate the optimum depth of cut, the values of the efficiency factor η must be known. η was estimated using data from graphs of cutting depth vs. energy density obtained experimentally, and the results have been presented in previous publications [2, 12]. The "blind" cutting model which resulted from the theoretical analysis presented in this paper allows predictions of the depth of cut and the efficiency factor η. The materials studied were primarily ceramics (porous and non-porous Al_2O_3, SiC).

Depths of cut in Al_2O_3 predicted by the theoretical model for "blind" cutting are shown in Figure 6. A comparison of the predicted depths with experimental results show that actual cuts have depths 10% to 30% of those predicted by using different values for the temperature T_k.

Figure 6 shows predictions of cutting depths in Al_2O_3 for a 1000 W laser beam with a focussed spot size of 0.013 cm using various values for the temperature T_k. It can be seen that the upper temperature limit more closely approximates the actual behavior.

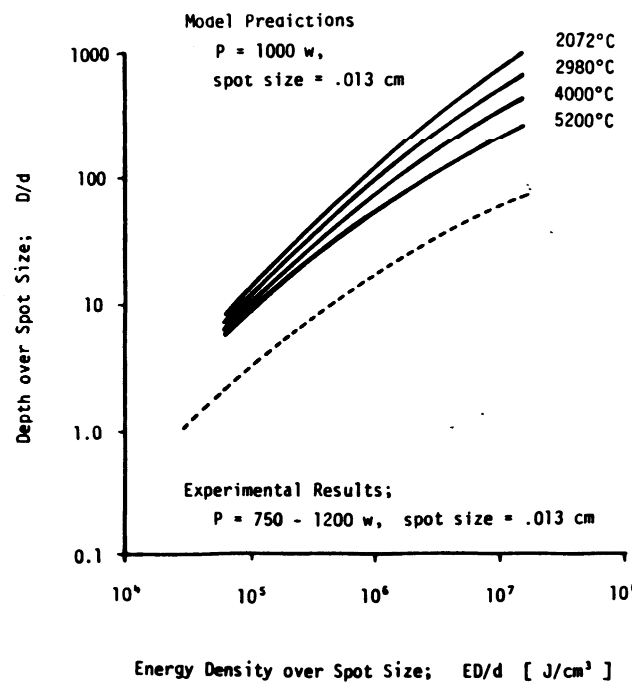


Figure 6: Theoretical and Experimental Results of Laser "Blind" Cutting in Al_2O_3

Figure 7 shows predictions of cut depths in Al_2O_3 using a 0.015 cm spot and T_k = 2,900° K temperature at different laser powers, 100W, 1,000W, and 10kW.

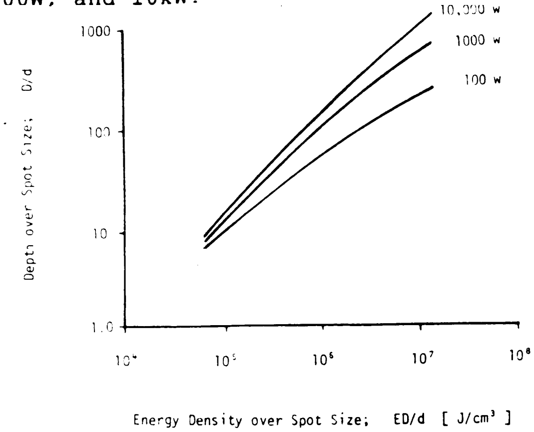


Figure 7: Theoretical Depth of "Blind" Cut in Al_2O_3 for Various Laser Powers

The effect of increasing laser power on the total material removal rate for the laser lathe is two-fold. First, by increasing laser power, the rate of energy delivered to the workpiece is increased. In other words, a 10kW laser will cut approximately ten times faster to the same depth as a 1kW laser. Second, when the laser power is increased, material is heated more rapidly in the vicinity of the spot and has therefore less time to conduct heat into the sides and bottom of the kerf. The increased energy efficiency for this case is shown in Figure 7. The model predicts that with a spot size of 0.0125 cm, a 10kW laser can make a 1 cm deep cut not ten times, but sixty times faster than a 1kW laser, provided a sufficiently strong gas jet can be applied to the workpiece.

DIMENSIONAL ACCURACY OF "BLIND" LASER CUTTING

The industrial application of the new machine tool requires the optimization of dimensional accuracy and surface quality of "blind" cuts. The objective is to obtain cuts with maximum wall straightness (no taper), minimum kerf width, and high surface quality. Low surface quality in "blind" laser cutting is the result of resolidifiction of the melt for materials such as ceramics and steel and thermal damage for GRP composites.

The profile and quality of "blind" laser cuts depend on combinations of the following factors:

a) Beam spatial profile

b) Beam polarization

c) Spot size/Depth of focus

d) Position of focal point with respect to the workpiece surface

e) Adjustment of the focal point with increasing depth of cut

f) External factors for enhancing material removal (e.g., gas assist)

g) Surface speed

The purpose of this experimental program is the determination of the influence of the above factors on the dimensional accuracy and surface quality of the laser cuts. Although this subject is still under investigation, the experimental work for the estimation of the efficiency factor η has provided results for effects of two factors, namely the supersonic gas assist and the surface speed.

The effect of using a supersonic nozzle to enhance material removal is illustrated in Figure 8. A comparison of profiles I, II, and III, and IV shows the effect of the high speed gas jet on the wall straightness, material removal, and cutting depth.

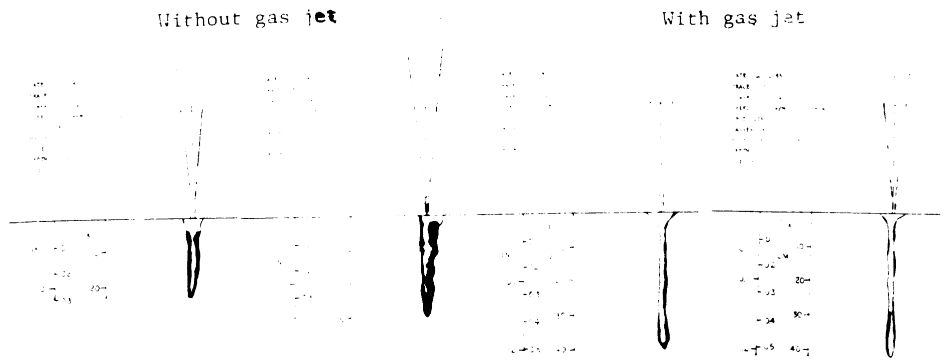


Figure 8: Effect of a High Velocity Gas Jet on Dimensional Accuracy

High surface speed, v, was also found to increase the quality of "blind" laser cuts. Figure 9 shows a series of cut profiles obtained with the same experimental conditions, with the exception of variable speed. A comparison of these profiles shows a dramatic decrease in kerf width, tapering, and resolidification of molten material with increasing speed.

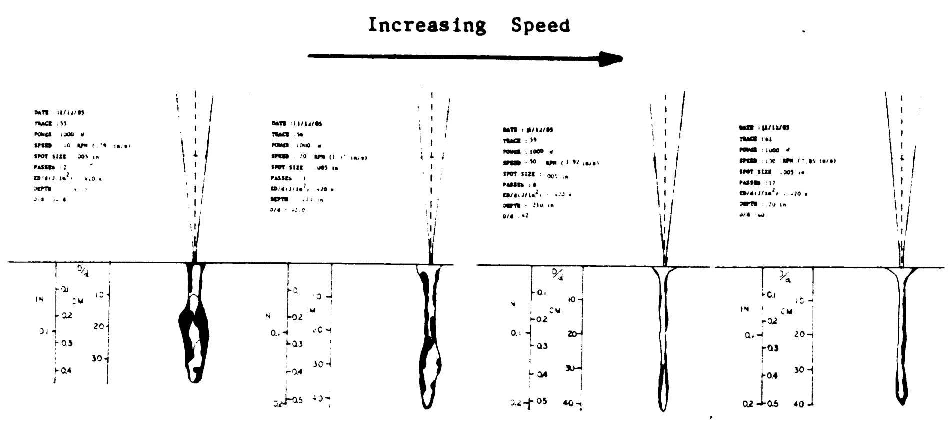


Figure 9: Effect of Surface Speed on Dimensional Accuracy

CONCLUSIONS

A new laser machining process, laser turning, has been suggested. The process utilizes two laser beams and creates intersecting kerfs on the workpiece. The optimization of the material removal rate of the process requires an understanding of the laser cutting mechanism, particularly that of "blind" cutting. An attempt has been made to model "blind" laser cutting using heat balance equations in order to predict the depth of cut and optimize the process. The preliminary model has been compared with experimental results. The dimensional accuracy and surface quality of the laser cuts have also been considered.

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