Article has been reported and discussed at 17th International Conference on Advanced Laser Technologies, ALT09, 26 September – 01 October 2009, Antalya/Turkey.

EFFECT OF CO_2 LASER FOCUSING ON GROOVE CUTTING INTO STEEL SURFACES

SULEYMAN BIYIKLI[1] AND JALE YILMAZKAYA SUNGU[2]

[1] *Mechanical Engineering Department, Okan University, 34959 Istanbul /Turkey*

[2] *Faculty of Arts and Science, Department of Physics, Kocaeli University, 41380 Kocaeli /Turkey*

High power CO_2 lasers with power outputs of 20 kW or more are being manufactured with such a power it is possible to build CNC machining centers to machine metals such as austenitic steels. Effect of lens focusing on evaporative laser groove forming on steel parts with a moving continuous wave laser is described by solving a heat transfer model. A three dimensional heat transfer model which was developed by Biyikli and Modest[13] subject to a number of assumptions such as negligible convective losses, no multiple reflections within the groove, and negligible beam channeling is modified for carbon steels for this study. This model is solved to analyze the lens focusing effects on the laser groove-cutting of steels. Evaporative removal of steel is achieved by heating the steel surface with a high-power CO_2 laser. The laser beam is highly-concentrated Gaussian Continuous-Wave at TEM_{00} mode and it is focused by a lens through which the laser beam passes and behind which it converges to a minimum beam waist and subsequently expands. The resulting non-linear partial differential equations were solved numerically by an explicit-implicit method. The thermal properties of steel which are available in the literature are used in this model to study the focusing effects on the kerf geometry for a given scanning speed and laser power. The results of this model are used to investigate the effect of lens focusing on the groove depth, thickness, and shape for some typical laser parameters such as lens focal position, laser power, and scanning speed.

1. INTRODUCTION

High power CO_2 lasers have been used as a tool for material processing such as welding, trimming, scribing, cutting in many different industries. With the concentrated energy of the $C0_2$, at the focal point of the lens it is possible to heat, melt, and vaporize any known material including stainless steel. Laser cutting have many advantages over conventional cutting techniques which include high productivity, narrow kerf width, low roughness of cut surfaces, minimum metallurgical distortion, easy integration with the CNC machines, cutting complex geometries, non contact process for reducing vibration, and eliminating all the problems related to the cutting tools [1-3]. Laser cutting is a thermal process in which a cut kerf (slot or groove) is formed by the heating action of a focused traversing laser beam. The laser cutting process types, defined according to their dominant transformation process, include: laser fusion cutting (inert gas cutting), laser oxygen cutting and laser vaporization cutting. The laser fusion cutting process, also called inert gas melt shearing, is based on transformation of the material along the kerf into the molten state by heating with laser energy and the molten material is blown out of the kerf by a high-pressure inert gas jet. The principle of laser oxygen cutting is that the focused laser beam heats the material in an oxidizing atmosphere and ignites an exothermic oxidation reaction of the oxygen with the material which in turn improves the laser cutting process by providing additional heat in the cutting zone resulting into higher cutting speeds compared to laser cutting with inert gases. During laser vaporization cutting, the material is heated beyond its melting temperature and eventually vaporized. A process gas jet is used to blow the material vapor out of the kerf to avoid precipitation of the hot gaseous emissions on the workpiece and to prevent them from condensation within the developing kerf. Laser vaporization cutting has the lowest speed among other methods; however, it is suitable for very precise, complex cut geometries [4 -5]. The laser cutting parameters are dependent on the beam wavelength, power, beam quality, polarization, thermal properties and thickness of the material to be cut, continuous wave (CW) or pulsed laser power, focal length of the lens, focal position of the lens relative to material surface, and the cutting speed [6].

Mathematical investigations in the area of laser material processing have treated cases with and without phase change and a variety of irradiation or source conditions have been studied both theoretically and experimentally. Material removal from the top surface of a solid by a high intensity laser beam was analytically treated by Dabby and Paek [7]. They calculated the material removal rate by vaporization from the solid surface and the temperature profile in the solid. Cline and Anthony [8] derived a model for laser heating and melting of materials for a Gaussian source moving at constant velocity for which they calculated the temperature distribution and depth of melting zone as a function of laser beam diameter, velocity and power. A three-dimensional heat transfer model was developed by Mazumder and Steen [9] for a laser beam striking the surface of an opaque substrate moving with a uniform velocity. The model was solved numerically for temperature distribution and melt depth. A model developed by Modest and Abakians [11] studied the formation of a groove by evaporation on a moving semi-infinite solid. Most of the analytical models reported in the literature assumed parallel laser beams which is a reasonable assumption only when there is no focusing of the beam, or when the focal length of the lens is many times the depth of the groove. In practical applications, material processing is achieved by melting or evaporating material with a Gaussian laser beam, which is focused by a lens to a small spot size around its focal point in order to increase the intensity of the laser beam. The radius of the focused beam waist and subsequent expansion of the beam depend on the characteristics of the laser beam as well as the type of lens being used. Both beam waist and expansion rate have profound effects on the size and shape of the laser cuts. Bar-Isaac and Korn [12] used a three-dimensional moving heat source model to describe the effect of a focused laser beam in the drilling process. They studied the effects of changing focal position of the beam on the motion of the evaporation surface. Biyikli and Modest [13] studied the evaporative cutting of a semi-infinite material with a moving focused continuous-wave laser by solving numerically the non-linear partial differential equations. The results of these solutions for groove depth and shape were presented for a variety of laser and solid parameters. The partial differential equations were non dimensionalized and solved for general cases which did not apply for any materials. In the present work, evaporative groove forming were studied for austenitic stainless steel (grades AISI 304 and AISI 316). . The effect of focusing parameters such as position of lens focal point above or below the surface, minimum beam radius, and material removal rate are investigated.

2. THEORETICAL ANALYSIS

Steel groove cutting is achieved by evaporating steel with a focused Gaussian laser beam as a heat source. A Gaussian laser beam at TEM_{oo} mode is focused by a lens through which the laser beam passes and behind which it converges to a minimum beam waist around the focal point of the lens, as shown in Figure 1. In order to develop a mathematical model the physical description of the problem is given as follows; a focused Gaussian laser beam strikes the surface of an opaque semi-infinite steel material moving in the x-direction with a constant velocity as shown in Figure 1. There are three different regions on the surface of the material. Region I is that part of the surface that is still too far away to have reached evaporation temperature or too far away on the side to even reach evaporation but it is heating; Region II is the area close to the beam center where evaporation takes place; and finally, Region III is the surface where evaporation has been completed but it is cooling off.

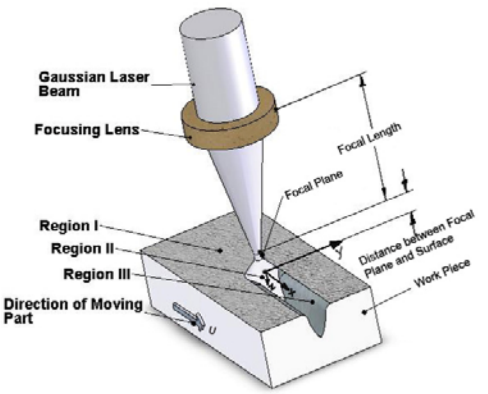

Fig. 1. Evaporative laser groove cutting by using a focusing lens with three different regions

Laser beam strikes with an intensity, F, to the surface of the material at an angle and starts evaporating and forming the groove which can be better visualized in Figure 2. The radius of the beam reaches to its minimum value at the focal plane and is expressed as the focal point radius, R_o. Distance between the focal plane and the surface is expressed as, w, can be on the surface, above the surface, or below the surface. Laser beam intensity can be calculated by using $F = P/\pi R^2(z)$ where P is the laser power, and the R(z) is the beam radius. Laser beam is striking at an angle when the groove is forming. Vector components of the laser beam intensity F_x, F_y, F_z, and F_r are also shown in Figure 2.

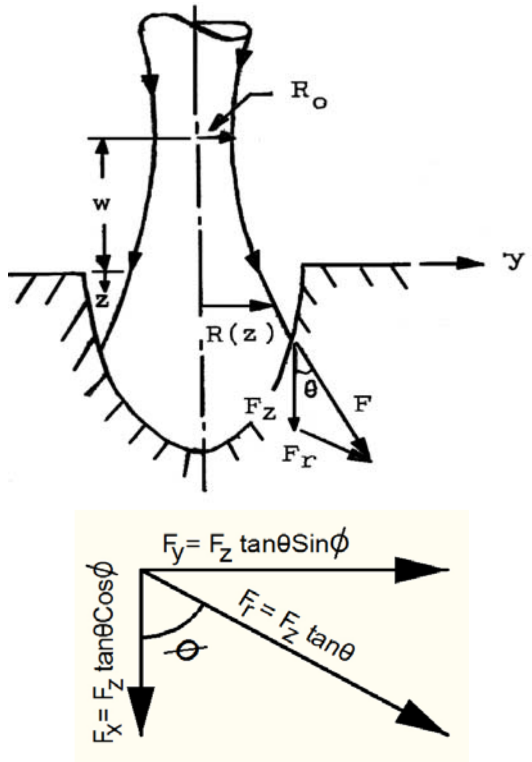

Fig.2. Evaporative laser cutting terminology used in the equations.

R (z) is the laser beam radius away from the focal plane of the beam. An expression for the laser beam expansion, R (z), is given by Self [14] as;

$$R(z) = R_o \left[1.0 + \left(\frac{w+z}{\pi R_o^2 / \lambda} \right)^2 \right]^{1/2} \tag{1}$$

Laser beam intensity at the beam focal point can be calculated by using $F_o = P/\pi R_o^2$ since the beam is striking at an angle when the groove is forming and also as the beam expanding, the beam intensity can be expressed by using the following equation;

$$\vec{F}(x,y,z) = (\vec{k} + \tan\theta\cos\phi\,\vec{i} + \tan\theta\sin\phi\,\vec{j})\; F_o \frac{R_o^2}{R^2(z)} e^{-(x^2+y^2)/R^2(z)} \tag{2}$$

where $\vec{i}$, $\vec{j}$, $\vec{k}$ are the unit vectors in the x, y, z directions, respectively, after evaluating the angles by using analytic geometry, laser beam intensity can be written as;

$$\vec{F}(x,y,z) = \left[\vec{k} + \frac{w+z}{\left(\pi R_o^2/\lambda\right)^2 + (w+z)^2} \left(x\,\vec{i} + y\,\vec{j} \right) \right] F_o \frac{R_o^2}{R^2(z)} e^{-(x^2+y^2)/R^2(z)} \tag{3}$$

The heat transfer model is developed by using the following assumptions, the more detailed discussion of the assumptions are given in reference [13].

I. The solid moves at constant velocity.
2. The solid is isotropic with constant thermal properties.
3. The material is opaque, i.e., the laser beam does not penetrate appreciably into the medium, with constant absorptivity.
4. Change of phase of the medium from solid to vapor occurs in one step at a single evaporation temperature.
5. The evaporated material does not interfere with the laser beam reaching the surface.
6. Multiple reflections of laser radiations within the groove are neglected.
7. Evaporation occurs as a quasi-steady laser cutting, for this case, the temperature does not change with time with respect to coordinate systen attached to the moving heat source. Experimental results indicate that a state is reached when an observer positioned at the heat source or moving origin detects no change in the temperature distribution around the source [10].

By using the assumptions and a similar derivation developed by Modest and Abakians [11], the heat transfer model is governed by the following equation,

$$\rho c u \frac{\partial T}{\partial x} = k\nabla^2 T \tag{4}$$

Subject to the boundary conditions;

$$x \to \pm\infty,\ \ y \to \pm\infty,\ \ z \to +\infty,\ \ T \to T_\infty$$

and at the surface, z=0;

$$\alpha(\vec{F}.\vec{n}) = -\rho h_{ig} u(\vec{i}.\vec{n}) - k(\vec{n}.\nabla T) \tag{5}$$

Where T is the temperature in the material, and u is the velocity in the x - direction. The boundary condition at the surface is obtained from energy balance on a surface element. Modest and Abakians [11] showed that the influence of convection and radiation losses on groove depth and shape is small, and for that reason it is assumed here that heat losses to the outside are negligible. The unit surface normal, $\vec{n}$, is pointing into the medium and is given by the following equation;

$$\vec{n} = \frac{\frac{\partial s}{\partial x}\vec{i} + \frac{\partial s}{\partial y}\vec{j} + \vec{k}}{\sqrt{1 + \left(\frac{\partial s}{\partial x}\right)^2 + \left(\frac{\partial s}{\partial y}\right)^2}} \tag{6}$$

The boundary condition at the surface for Region I where there is no evaporation yet but it is heating by the laser beam can be expressed as;

$$\alpha F_o \frac{R_o^2}{R^2(0)} e^{-(x^2+y^2)/R^2(0)} = -k\frac{\partial T}{\partial z} \tag{7}$$

$$x < x_{\min}(y)$$

Where F_o is the intensity of the laser beam at beam center, R_0 is the effective laser beam radius at the focal plane, R(0) is the beam radius at the surface, z=0, which does not have the same value as R_0 when the beam is below or above the surface. In this equation α is surface absorptivity, $x_{min(y)}$ is the location where evaporation commences. Then the boundary conditions at the surface for Region II where evaporation is taking place are expressed as;

$$\left[1 - \frac{w+s}{\pi R_0^2/\lambda + (w+s)^2}\left(x\frac{\partial s}{\partial x} + y\frac{\partial s}{\partial y}\right)\right]\alpha F_o \frac{R_o^2}{R^2(s)} e^{-(x^2+y^2)/R^2(s)}$$
$$= \rho h_{ig} u \frac{\partial s}{\partial x} - k\left(\vec{n}.\nabla T\right)\sqrt{1 + \left(\frac{\partial s}{\partial x}\right)^2 + \left(\frac{\partial s}{\partial y}\right)^2}$$
$$T = T_{ev},\ \ z = s(x,y),\ \ x_{\min} < x < x_{\max}(y) \tag{8}$$

where s is the local groove depth, n is the unit surface normal pointing into the medium, and h_{ig} is the heat of sublimation of steel. Similarly, the boundary condition for Region III where the groove is fully established, laser beam moved away and there is no evaporation taking place but the material is cooling off.

$$\left[1 - \frac{w+s_\infty}{\pi R_0^2/\lambda + (w+s_\infty)^2}\, y\frac{\partial s_\infty}{\partial y}\right]\alpha F_o \frac{R_o^2}{R^2(s_\infty)} e^{-(x^2+y^2)/R^2(s_\infty)}$$
$$= -k\left(\vec{n}.\nabla T\right)\sqrt{1 + \left(\frac{\partial s_\infty}{\partial x}\right)^2 + \left(\frac{\partial s_\infty}{\partial y}\right)^2}$$
$$z = s_\infty(y),\ \ x > x_{mac}(y) \tag{9}$$

3. METHOD OF SOLUTION

Equations (1- 9 are solved by using an explicit-implicit numerical method. In this study, thermal properties of steel are used in the governing equations in order to study the effect of lens focusing on the size and shape of a groove formed by laser evaporation. Table 1 lists the thermal properties of carbon steels which are reported by many investigators [15-16], these properties were used during solution of the governing equations.

Table 1 Thermal properties of Carbon Steel (Steel 304)

Thermal Properties	Values and Units
Density (ρ)	7870 kg/m^3
Melting Temperature (T_m)	1808 K
Ambient Temperature (T_∞)	298 K
Evaporation Temperature (T_{ev})	3023 K
Specific Heat of Solid Material(c_{ps})	0.452 kJ/kg K
Specific Heat of Liquid Material(c_{pl})	0.800 kJ/kg K
Specific Heat of Vapor Material (c_{pv})	0.450 kJ/kg K
Latent Heat of Melting (L_m)	272 kJ/kg
Latent Heat of Evaporation (L_{ev})	6088 kJ/kg
Heat of Sublimation (h_{ig})	8015 kJ/kg
Thermal Conductivity (k)	27 W/mK
Surface Absorptivity (α)	0.80

There was no reported value for heat of sublimation for steels that is why; the following formula is used to evaluate the value of heat of sublimation of steel.

$$h_{ig} = c_{ps}(T_m - T_\infty) + L_m + c_{pl}(T_{ev} - T_m) + L_{ev} \tag{10}$$

Calculations were based on a $10.6\mu m$ wavelength 9.6 kW CO_2 laser with a beam size of 19 mm in diameter which has a focusing lens of 190 mm focal length that can reduce the beam size to $135\mu m$ in diameter at the focal plane, and the scanning speed of 8.5 cm/s.

While only the solution to Regime II is of interest Regime I must be solved first in order to provide the boundary between the two regimes, $x_{min}(y)$ and a beginning value for the conduction penetration depth. The equations for Regime I can be solved analytically and the solution for the surface temperature distribution is;

$$(T - T_\infty) = \left[\frac{3\alpha^2 P^2 e^{-(x^2+y^2)/R^2}}{4\rho cuk\pi^{3/2} R^3} \left[1 + erf\left(\frac{x}{R}\right) \right] \right]^{1/2} \qquad (11)$$

Solving for y as a function of x in Eq(1I) for $T= T_{ev}$ establishes the boundary between Regions I and II. The groove depth s(x,y) is found from the equations for Region II using the Region I solution as boundary conditions by using explicit-implicit numerical method as described in details Biyikli and Modest [13].

4. DISCUSSION OF RESULTS

When a beam is focused by a lens, the resulting beam waist and subsequent expansion of the beam depends on the characteristics of the laser beam as well as the type of lens being used. Figure 3 shows top view of evaporating zone under a laser beam striking to the surface of a flat steel part.

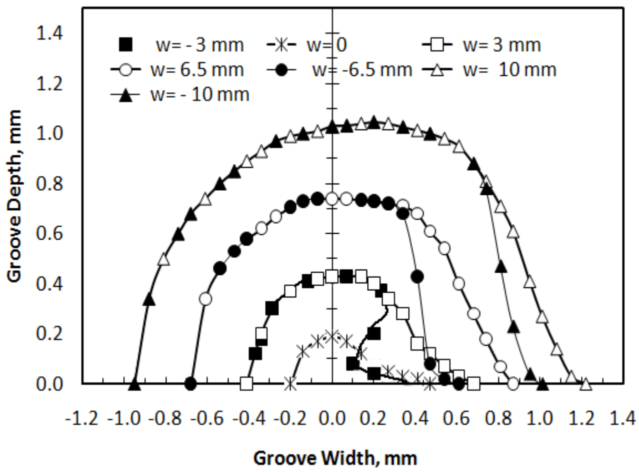

Fig. 3 Top view of the evaporation region when the beam focal point at different locations on the surface of the steel work piece.

The plots are actually symmetric around x-axis to give the complete view of the laser cut. It is seen that sizes and shapes of the evaporating zone change significantly with changing focal position of the beam on the material; w is negative for focal point of lenses below the surface of the material. The evaporating zone is smallest where the beam is focused on the surface I (w = 0). Changing the focal point of the lens above or below the surface of the material increases the area of evaporating zone.

The influence of beam waist position on fully developed groove shape and depth is shown in Figure 4 for focal points below the surface of the steel work piece. It is observed that the depth of the cuts increases and passes through a maximum when the beam is focused slightly inside the material. This type of behavior has also been observed by Bar-Isaac and Korn [12] for laser drilling. When the focal point is moved further into the material the groove becomes shallower. The increase in the groove depth by focusing the beam slightly inside the material is apparently due to better focusing of the laser energy in the center of the evaporating groove hence utilizing the energy more efficiently for evaporation rather than for conduction; further moving the focal point into the material diverges the beam in the evaporating zone and increases the conduction losses.

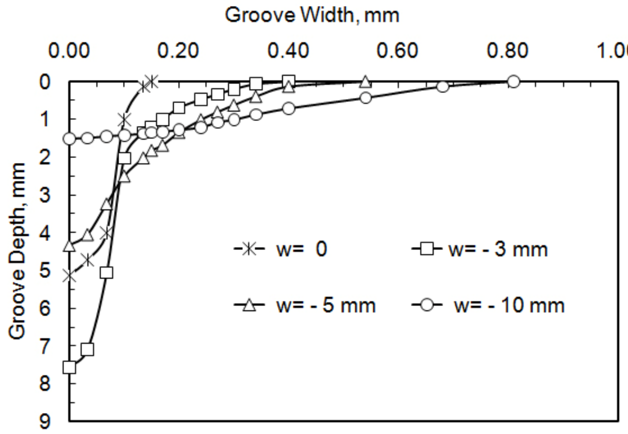

Fig.4. Effect of focal positions on the groove cross-section when focal point is in the steel, w shows the distances between the focal point of the lens and top surface of the steel.

Changes in the fully developed groove shape and depth when the beam is focused above the surface of the material are shown in Figure 5. The groove gets shallower and wider when the focal plane is moved up from the surface of the material, since the laser energy is less concentrated everywhere within the evaporation zone. As can be seen in Figures 4 and 5, the narrowest cuts are obtained when laser beams focused on the surface. This can be an important point to remember for some laser cutting operations.

The variation of fully developed maximum groove depth as a function of beam focusing distance, w, is shown in Figure 6 for different beam expansion rates. Maximum groove depth for parallel beams (w = 0) staying at focal point diameter is of course ideal case, in reality laser beam expands after the focal plane. In practice parallel beams coming from a laser are unfocused and are therefore have large beam diameters depending on the laser characteristics and are rarely strong enough to cause evaporation. In order to evaporate a material these beams need to be focused to a small diameter thus the parallel beam in Figure 6 corresponds to an ideal beam which has a diameter equal to the diameter of a focused beam at the focal plane showing a case of a lens with an infinite focal length.

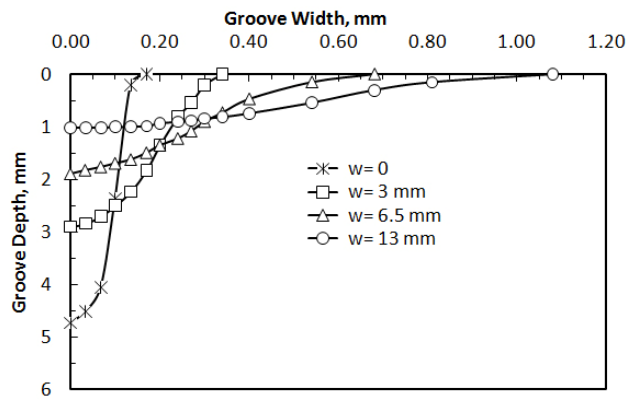

Fig.5. Effect of focal positions on the groove cross-section when focal point is above the steel surface, w shows the distances between the focal point of the lens and top surface of the steel.

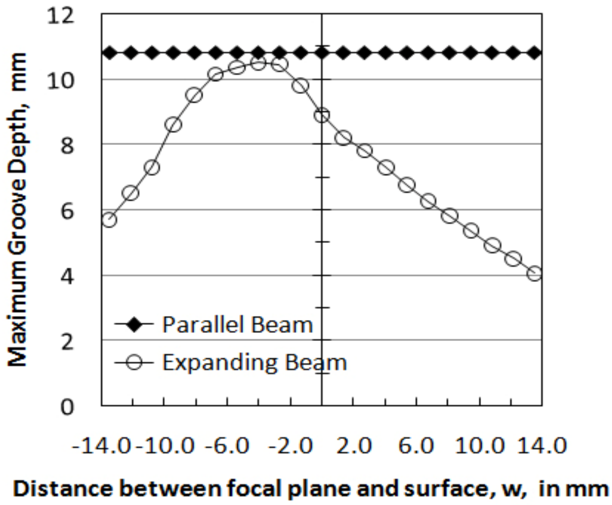

Fig.6. Variation of maximum groove depth as a function of focal plane position which can be above, below, or on the surface for parallel and expanding beams.

Figure 7 shows maximum groove depth as a function of laser power (or decreasing laser power) for different beam focusing rates. As expected for constant scanning speed the groove depth decreases significantly with decreasing laser power. This effect is the same for all focusing conditions. The effect of increasing laser speed on the groove depth for constant laser power is very similar to the variation of the groove depth in Figure 7 (not shown here).

Evaporated material removal rate varies with the distance between the lens focal plane and the surface of the work piece as shown in Figure 8.

The straight line in Figure 8 shows the maximum possible material removal rate meaning all the laser power is used just to evaporate steel, there are no other losses. When the lens is focused above or below the surface of the steel gives more material removal rate, when lens is slightly focused inside the surface (w= - 3 mm) gives the highest removal rate.

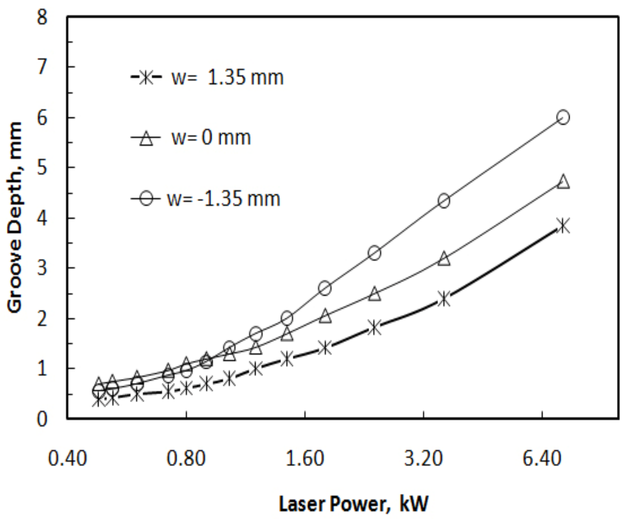

Fig.7. Variation of Maximum Groove Depth with laser power at a scanning speed of 8.5 cm/s.

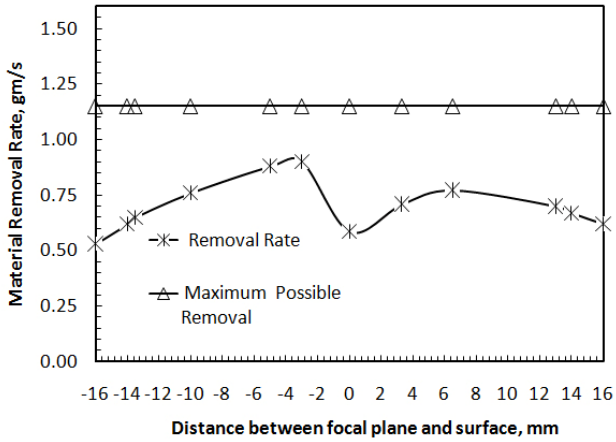

Fig.8. Variation of material removal rate with the distance between lens focal plane and the surface of the work piece

5. CONCLUSIONS

A heat transfer model for evaporative cutting of a semi-infinite body with a moving continuous wave laser has been solved numerically to investigate the effects of beam focusing on the size and shape of a groove. The study of the results indicated some interesting aspects. The depth of the groove increases and passes through a maximum when the beam is focused slightly in the material. The groove depth decreases when the beam is focused above the surface of the material. The groove depths can be increased by using lenses with long focal lengths. Longer focal length lens give a larger minimum beam radius at focal plane. Smallest width cuts are obtained when the beams are focused exactly on the surface.

Heat Affected Zone(HAZ) is defined as the temperature at which the material will experience a change in properties, for carbon steels the critical temperature is eutectoid temperature which is at 723^0 C . Heat Affected Zone for carbon steels for the evaporating zone can be upto 2.4 mm from the evaporating surface.

6. NOMENCLATURE

c - specific heat, kJ/kg.K
F_o - laser intensity at center of a beam, W/m^2
F_x, F_y, F_z, F_r are the components of the intensity, W/m^2
h_{ig} - heat of sublimation, kJ/kg
n - unit vector normal to the groove
k - thermal conductivity, J/s.m.K
P - laser power, W
R - effective laser beam radius, mm
R_0 - laser beam radius on focal plane, mm
s - groove depth, mm
s_{max} - maximum groove depth, mm
s_∞ - established groove cross section , mm
T_{ev} - evaporation temperature, K
T_∞ - ambient temperature, K
u - laser scanning speed, cm/s
w - distance between the focal plane and surface, mm
α - absorptivity
ρ - density, kg/m^3
λ - laser wave length, μm

[1]. *N.Rajaram, J. Sheik-Ahmad and S. H.Cheraghi,* "CO_2 laser cut quality of 4130 steel", International Journal of Machine Tools & Manufacture Volume 43, 2003, pp. 351-358.

[2]. *I.P. Shkarofsky,* "Review on Industrial Applications of High Power Laser Beams III", RCA Review, Vo1. 36, 1975, pp. 338-368.

[3]. *H.Golnabi and M.H. Mahdieh*, "Trend of laser research developments in global level", Optics & Laser Technology, Volume 38, Issue 2, 2006, pp. 122-131.

[4]. *D.Petring*, "Laser Cutting", LIA Handbook of Laser Materials Processing, First Edition, 2001, Laser Institute of America, ISBN 0-912035-15-3, pp. 425-433.

[5]. *J.Powell*, "CO_2 Laser Cutting", 1993, Springer Verlag, ISBN 3-540-19786-9, pp. 83-184.

[6]. *J.C.Ion*, "Laser Processing of Engineering materials", ISBN 0 7506 6079 1, pp. 347-365.

[7]. *F.W. Dabby, and U. Paek*, "High Intensity Laser-Induced Vaporization and Explosion of Solid Material", IEEE J. of Quantum Electronics, Vol. QE-8, No.2, 1972, pp. 106-111.

[8]. *H.E. Cline, and T.R.Anthony,* "Heat Treating and Melting Material with Scanning Laser or Electron Beam", Journal of Applied Physics, Vol. 48, No.9, 1977, pp. 3895-3900.

[9]. *J. Mazumder and W.M.Steen,* "Heat Transfer Model for CW Laser Material Processing", Journal of Applied Physics, 51(2), 1980, pp. 941-947.

[10]. *E.Kannatey-Asibu,* "Principles of Laser Materials Processing", Wiley, 2009, pp231-280.

[11]. *M. F. Modest and H.Abakians,* "Evaporative Cutting of a Semi-Infinite Body with a Moving CW Laser", ASME Journal of Heat Transfer , Vol. 108, 1986, pp. 602-607.

[12]. *C.Bar-Isaa, and U.Korn,* "Moving Heat Source Dynamics in Laser Drilling Process", Appl. Phys., Vol. 3,1974, pp. 45-54

[13]. *S.Bıyıklı and M.F.Modest,* "Beam Expansion and Focusing Effects on Evaporative Laser Cutting", Journal of Heat Transfer, 110, (1988), 529-532.

[14]. *A.S. Self,* "Focusing of Spherical Gaussian Beams", Applied Optics, Vol. 22, No 5, 1983, pp 658-661.

[15]. *M.J. Hsu and P.A.Mollian,* " Thermo chemical modeling in $C0_2$ laser cutting of carbon steel" Journal of Materials Science 29 (1994) 5607-5611.

[16]. *B.S. Yilbas, S.B. Mansoor, R. Mansoor,* "Laser pulse heating: Cavity formation into steel, nickel and tantalum surfaces", Optics & Laser Technology 40 (2008) 723–734.