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Two Dimensional Finite Element Modeling Of Single Pulse Laser Drilling

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Abstract- A Finite element model of transient temperature distribution problem is developed. As the Laser is a powerful beam used for cutting complex profiles and drilling micro holes in wide range of materials. Very small diameter micro holes (up to 3μm) can be drilled with high aspect ratio. The effect of various input parameters: like, pulse widths, pulse frequency, radius of laser beam and peak power are studied. And the temperature variations across the depth and at the radial directions are developed. The temperature distributions are examined by using the finite element software Ansys. . The developed Fem-based thermal model is validated with previous research. The results predicted by FEM modeling shows that with increase in pulse width the hole taper decreases but the entrance diameter and exit diameter of the hole increases. All the material, time and response dependent non linearity are included.

Keywords- **Axis symmetric transient model, Finite element method (FEM), Laser drilling.**

I. INTRODUCTION

The major LBM configurations are: drilling (1-D), cutting (2-D) and grooving, turning and milling (3-D), and micromachining of different work piece materials. Laser beam drilling has become the accepted economical process for drilling thousands of closely spaced holes in structures. Two types of laser beam drilling exist: trepan and percussion laser beam drilling [1]. Trepan drilling involves cutting around the circumference of the hole to be generated, whereas percussion drilling 'punches' directly through the work piece material with no relative movement of the laser or work piece. The inherent advantage of laser percussion drilling process is the reduction in processing time [2]. Laser beam cutting and grooving operations have found applications in punching, cut off and marking of metals, ceramics and plastics. Laser beam cutting is superior to any other cutting methods. In a manufacturing industry, fabrication of small diameter hole (< 1 mm) in advance engineering materials have always been a challenging task. [3].
Nickel-based super alloys are some of the most difficult material to machine due to their high hardness, high strength at high temperature, tendency to react with tool materials and low thermal diffusivity. Inconel 718, with composition as mentioned in (Table 1) and having material properties (Table 2) and thermo-physical properties (Table 3) [1], finds wide application in (i) air craft gas turbines e.g., combustion chamber, blades, vanes, etc. (ii) steam turbine power plants e.g., blades, stack gas reheaters (iii) reciprocating engines e.g., turbochargers, exhaust valves, etc., (iv) heat treating equipments and (v) nuclear power systems. [4]. In the last years, laser beam drilling became increasingly for many technical applications as it allows the contact less production of high quality drill holes [5]. So far, mainly short laser pulses are of industrial relevance, as they offer a good compromise between precision and efficiency and combine high ablation efficiency with low thermal damage of the work piece. Moreover, lasers with short wavelength are more suitable for production of small diameter holes with high aspect ratio. Therefore, the solid state pulsed Nd:YAG laser is widely used for the LBPD process, because it emits high laser intensity with very good focusing characteristics [6]. The physical process involved in LBPD indicates that the accuracy and quality of laser drilled holes are mainly determined by the content of liquid phase and the uncontrollable distribution of molten materials in the laser-drilled hole [7]. The thickness of the molten layer depends on the energy and duration of the laser pulse. Therefore, pulse width (t), pulse frequency (f) and peak power (Pp) has been chosen as the input process variables [8]. Moreover, the amount of total laser energy required to produce a through hole also depends on the geometrical dimensions of the work piece; hence, the thickness of sheet (t_h) has also been considered as an input process variable for the complete thermal analysis of LBPD.Ansys is one of the most advanced large-scaled finite element software in the world, it possesses robust computing function and extensive simulated performance and it has a large number of different kinds of element models, material models and analytic processes, especially its good nonlinearity mechanical analysis function is at the world leading level. Finite element method was used to predict the temperature variation across the depth and along the radial direction of the hole during the laser drilling process. [9] ANSYS Parameter Design Language was used to model the Gaussian- distributed

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Table 1: Percentage chemical composition of Inconel 718

Fe	Ni	Cr	Cu	Al	Mo	Mn	Ti	Si	C	Cd+Ta
18.5	52.37	19	0.15	0.5	3.05	0.18	0.9	0.18	0.04	5.13

Table 2: Temperature dependent material properties of Inconel 718.

Temperature(K)	Density ($kg\ m^{-3}$)	Specific Heat ($J\ kg^{-1}\ K^{-1}$)	Thermal Conductivity ($Wm^{-1}\ K^{-1}$)
273	8240	425	11
473	8193	468	14
673	8130	511	18
873	8058	561	20
1073	7978	594	23
1273	7889	644	26
1473	7792	683	29
1673	7363	728	32
1873	7280	772	35

Table 3: Average thermo physical properties of Inconel 718.

Definition	Unit	Value
Melting range(T_m)	K	1533-1628
Density(ρ)	$Kg\ m^{-3}$	8240
Specific heat(C_p)	$J\ kg^{-1}\ K^{-1}$	439
Conductivity (K)	$W\ m^{-1}\ K^{-1}$	10.3
Latent heat of fusion (H_m)	Jkg^{-1}	231×10^3
Latent heat of boiling(H_v)	Jkg^{-1}	6444×10^3
Thermal diffusivity	$m^2\ s^{-1}$	2.85

Heat flux from the laser beam acting on the work piece. In addition, laser cutting was simulated at continuous wave (CW) and the temperature variations across the depth were investigated. Few research studies have been conducted on the thermal stress of laser cutting at different shapes and thicknesses of metals [10]. Previous research introduced a constant temperature heat source at the melting temperature of the material for the laser beam in the finite element simulation. In this study, a Gaussian-distributed heat source is adopted as the laser heat source in modeling laser cutting. The temperature and stress fields of the work piece are computed using finite element method (FEM) [11]. This model is also capable of predicting temperature variation across the depth. he objective of this work is to develop a finite element model for drilling a fine micro hole in a thin sheet of inconel and to study the variations of the output variables like entrance diameter, exit diameter, hole taper with respect to the input variable like pulse width keeping the peak power and pulse frequency of the laser beam as constant using the validated FEM based thermal model.

II. THEORY AND MODELLING

As mentioned earlier, laser drilling is a thermal cutting process. The laser beam is focused on the work piece which is heated locally. Some of the laser energy is absorbed by the material while the rest is reflected. The absorbed laser energy is then conducted into the material and is lost as heat through convection from the surface. The efficiency of laser energy absorbed by the material depends on the thermal and optical properties of the material as well as, the wavelength of the laser beam, its polarization, and the temperature of the work piece [12].

A. Laser heat source modeling

Heat source modeling is the most important part in the thermal analysis of laser drilling. Various beam shapes including Gaussian, circular, rectangular, etc., can be obtained by using the beam-shaping method for different kinds of applications in laser material processing [13]. Among these, the Gaussian energy distribution is the most preferred mode for laser cutting because a very small diameter can be focused, resulting in a higher power density [14].Due to the axisymmetric nature of the LBPD process, a small cylindrical portion of the sheet around the axis of the laser pulse is used as the domain (D) [Fig. 1]. The governing equation for determining the transient temperature distribution within the domain of axisymmetric sheet can be expressed using Eq. (1) [15] in domain ABCD.

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$$K(T)\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial T(r,z,t)}{\partial r}\right)+\frac{\partial^2 T(r,z,t)}{\partial z^2}\right]=\rho(T)\,C(T)\frac{\partial T(r,z,t)}{\partial t} \qquad (1)$$

Where, *T* is the transient temperature at *(r,z,t)*, t is the time, *k(T)* is temperature-dependent thermal conductivity, ρ(T) is the temperature-dependent density, *C(T)*is the temperature dependent specific heat of the sheet material in solid state, and *r* and *z* are the coordinate axes.

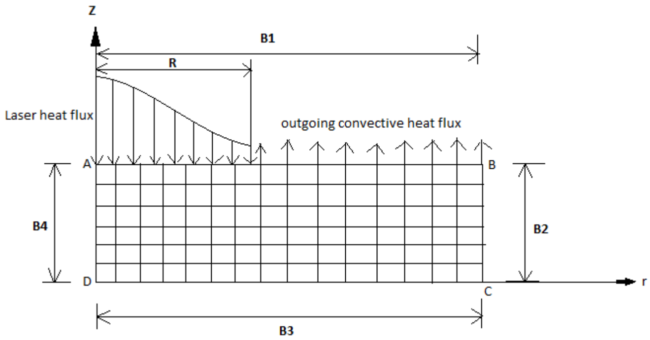

Fig 1.Thermal model of single pulse Nd: YAG laser drilling.

B. Finite element modeling

Assumptions:

(1) Laser beam is of Gaussian type in a continuous mode,
(2) Material moves at a constant relative velocity,
(3) Material is isotropic and opaque with constant thermal and optical properties,
(4) Material removal is a surface phenomenon and phase change from solid to vapor occurs in one step,
(5) Evaporated material is transparent and does not interfere with incident laser beam,
(6) Heat losses by convection and radiation from the surfaces to the environment can be approximated by using a single constant convection coefficient [16].

The initial temperature of the entire domain is equal to the ambient room temperature (T_0), i.e., T(r, z, 0) =T_0 in the domain ABCD at t=0. The energy transferred to the sheet as heat input serves as the thermal boundary condition on the top surface B_1.The boundaries B_2 and B_3 are considered to be at such a large distance that no heat transfer takes place across them. The net heat loss or gain across the boundary B_4 (axis of symmetry) is absolute zero. Therefore, the boundary conditions are:

$when\ 0 < t \le \tau$

$$\tau k(T)\frac{\partial T(r,z,t)}{\partial z}=\begin{cases} h(T(r,z,t)-T_0)\ for\ r>R\ on\ B_1 \\ q_{in} \qquad for\ r\le R\ on\ B_2 \end{cases} \qquad (2)$$

$when\ \tau < t \le t_p$

$$k(T)\frac{\partial T(r,z,t)}{\partial z}=h(T(r,z,t)-T_0)on\ B_1 \qquad (3)$$

$when\ t>0$

$$\frac{\partial T(r,z,t)}{\partial n}=0\ on\ B_2, B_3\ and\ B_4 \qquad (4)$$

Where, τ is the pulse width, t_p is the total pulse duration (i.e., on and off time), q_{in} is the amount of heat flux entering the sheet, *R* is the laser beam radius, *h* is the heat transfer coefficient, T_0 is the ambient room temperature, and direction *n* is outward normal to the boundary surface.

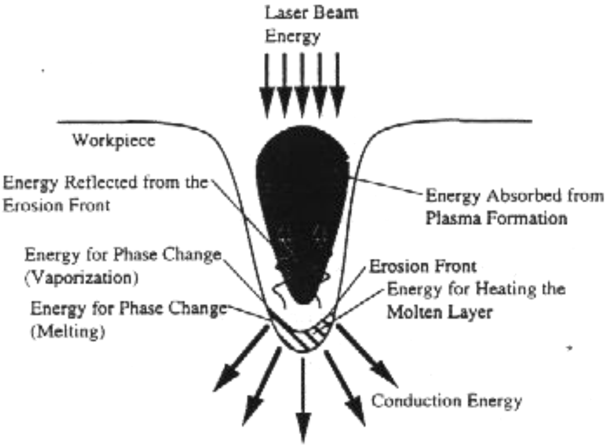

Fig 2: A complete Gaussian laser beam making hole in the work piece.

C. Heat flux input

Heat flux at a distance 'r' from the center of the laser beam on the surface of the sheet is given by [17]:

$$q_{in} = A_s \frac{2P_p}{\pi R^2} \exp\left(\frac{-2r^2}{R^2}\right) \qquad (5)$$

The change of laser beam radius with the depth can be evaluated as:

$$R = \frac{d}{2}\left[1 + \left(M^2 \frac{4\lambda(Z_m + f_c)}{\pi d^2}\right)\right] \qquad (6)$$

Where A_s is the absorptivity, P_P is the laser peak power, R is the effective beam radius, which varies with the depth of the hole due to defocusing, d is the beam diameter (500 mm), f_c is the focal length of lens (50 mm), z_m is the melt depth, and is the wavelength of the laser beam [18].

The value of P_P can be calculated by:

$$P_{p}(W) = \frac{Average\ laser\ power\ (W) \times 1000}{Repetition\ rate\ (Hz) \times Pulse\ width\ (ms)} \qquad (7)$$

Absorptivity of a material can be determined by:

$$A_s = \sqrt{\frac{4\pi c \epsilon_0 [1 + \alpha_r (T(r,t) - T_0(r,t))]}{\lambda \sigma_0}} \qquad (8)$$

Where,

ϵ_0 is the permittivity of vacuum, α_r is the coefficient of resistance of the sheet, λ is the wavelength of the Nd:YAG laser beam, c is the velocity of light and σ_0 is the target conductance at initial temperature. Table 4 shows the values of the above parameters for inconel 718.

Table 4: Electrical properties of Inconel 718.

Definition	Values
Permittivity of vaccume ($C^2 N^{-1} m^{-2}$) Cofficient of resistance (K^{-1}) Conductance ($\Omega^{-1} m^{-1}$)	8.85×10^{-12} 0.006 8.7×10^5

D.Temperature distribution model:

For the determination of temperature distribution, an initial domain of thicknesses of 0.04 mm with a radius of 2500 mm is used. The domains were discretized into eight noded quadratic serendipity elements. The nodal coordinates and connectivity matrices of the elements were obtained using ANSYS 13. Based on the results of the convergence test an element size of 6.25 X 6.25 μm was used for this work. The initial temperature of the sheet is taken as 298 K.

E.Hole taper calculation:

When a laser pulse irradiates the surface of a sheet, the temperature begins to rise and at the end of the pulse the volume of material having temperature more than the melting temperature (1533 K) of Inconel 718 is removed

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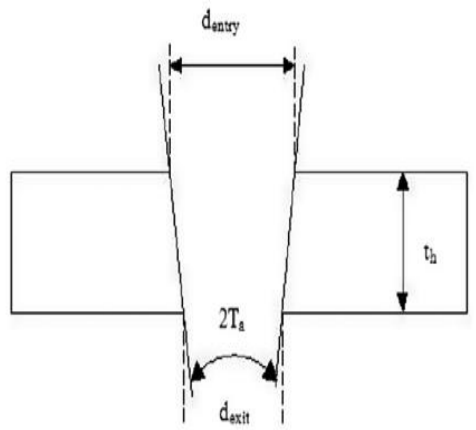
from the sheet to create a hole. The melt-isotherm is obtained from the result of temperature distribution. The diameter at the entry and exit side can be finally be obtained from the final melt-isotherm, and the T_a is calculated using Eq. (9), as shown in Fig. (3) [19].

$$T_a(degree) = tan^{-1}\left[\frac{d_{entry}-d_{exit}}{2t_h}\right] \times \frac{180}{\pi} \quad (9)$$



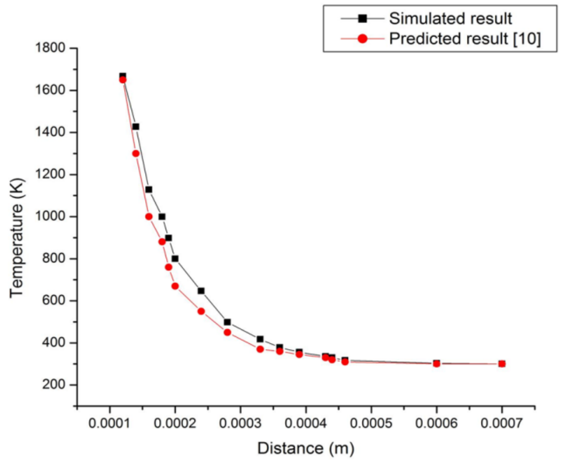


Fig 3: Schematic diagram of hole taper in thin sheet. **Fig 4: Temperature distribution along the r-axis**

III. RESULTS AND DISCUSSIONS

Laser drilling of Inconel sheet was modeled using the finite element method and the temperature distribution around the cut edges is predicted. As shown in the figure 5(a) after doing the convergence test before modeling as in 5 (b). Fig 4 shows the results predicted by the FEM model in terms of temperature at different values along radial direction have been compared with the simulated results obtained by conducting the modeling under same machining conditions. The temperature predicted by the developed model is in good agreement with the simulated result. The difference observed between the simulated and predicted values could be due to the non-inclusion of certain aspects in the developed model, like the formation of plasma, multiple reflection of laser beam inside the hole cavity, etc. ig 6 shows the temperature variation along the radial direction of work piece of four different pulse width i.e. 1.9 ms, 2.4 ms, 2.9 ms & 3.4 ms. Hence with the increase in pulse width, the temperature increases at different nodes, consequently increases the hole diameter.

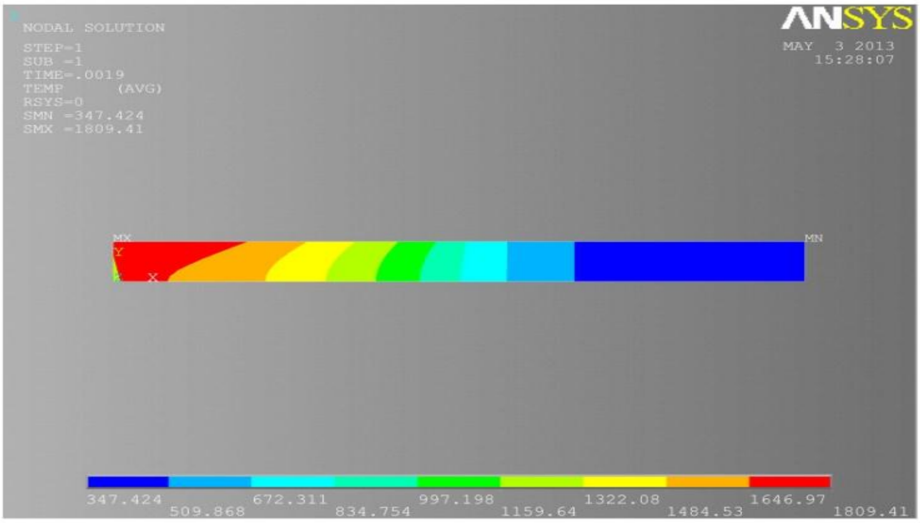


Fig 5(a): 2D view of temperature distribution around the hole surface once the cutting process is completed (temperature unit is K).

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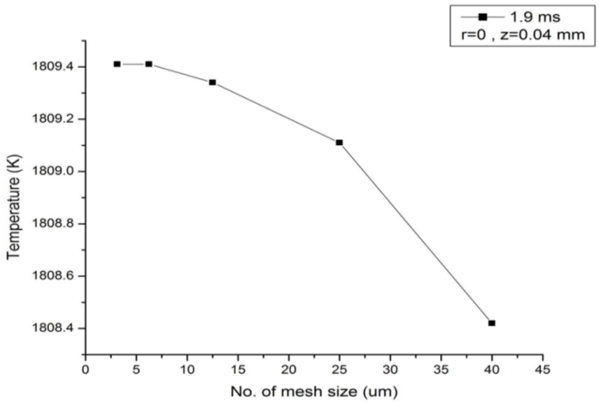

Fig 5(b): Results from convergence test.

Fig 7 shows the temperature variation across the depth of the work piece. Hence the temperature across depth increases with increase in pulse width. The graph shown in fig (8) & (9) explains the increase in entrance and exit diameter of hole with increase in pulse width by taking the peak power and frequency as constant value for same thickness of the work piece.

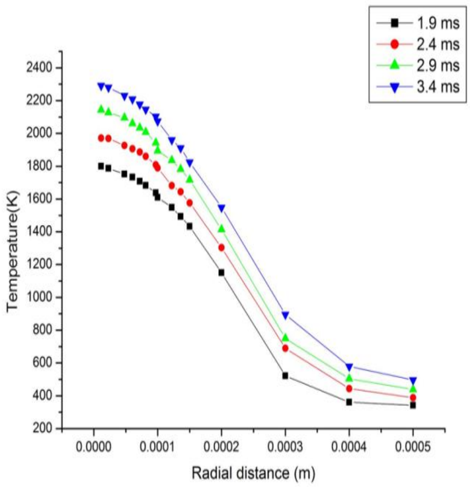

Fig 6: Temperature distribution along the radial direction.

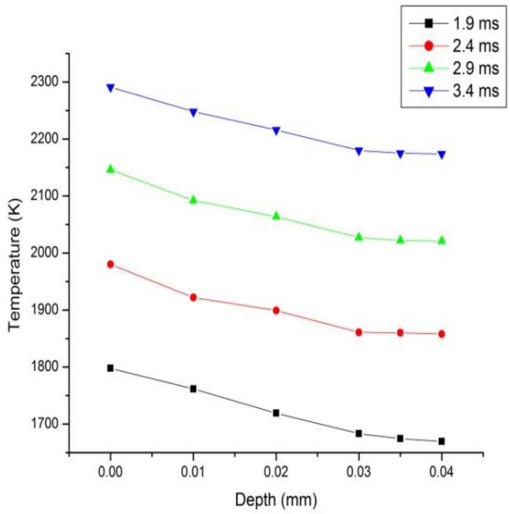

Fig 7: Temperature variation across depth

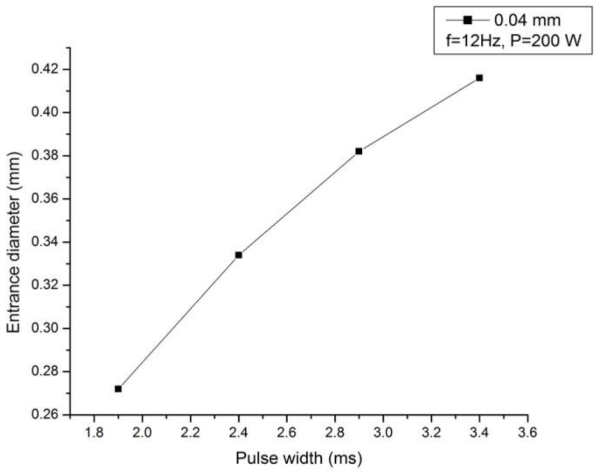

Fig 8: Variation of Entrance diameter with respect to pulse width, pulse frequency and peak power.

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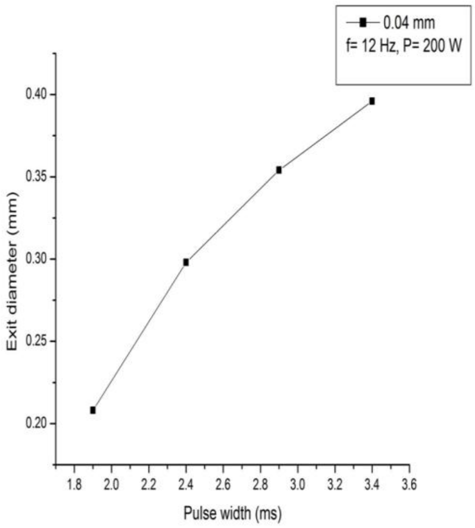

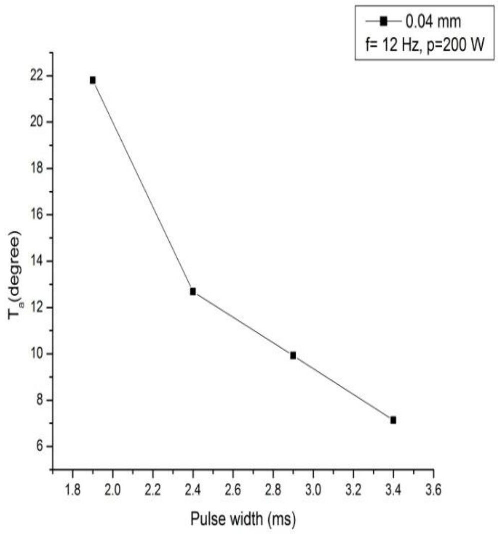

Fig 9 & 10: Variation of Exit diameter with respect to pulse width, pulse frequency and peak power, Variation of T_a with respect to pulse width, pulse frequency and peak power.

Fig 10 shows that the hole taper decreases with the increase in pulse width as the determination of T_a is important to evaluate the degree of cylindricality of a drilled hole with values close to zero corresponding to a better quality.

IV. CONCLUSION

In the present work a two dimensional finite element model is developed for drilling hole in thin sheet of Inconel-718 using Nd-Yag laser cutting process. The output predicted after modeling are plotted with the input variables and following results comes:

1. Temperature decreases along the radius as well as across the depth of the hole cavity after drilling.
2. Entrance diameter as well as exit diameter increases by increasing pulse width.
3. Hole taper decreases by increasing pulse width.

REFERENCES

[1] Mills KC. Recommended values of thermo physical properties for commercial alloys. Abington, U.K.: Wood head publishing Limited; 2002.

[2] Yilbas BS, Arif AFM, Abdul Aleen BJ (2009) Laser cutting of holes in thick sheet metals: development of stress field. Opt Laser Technol 47:909–916.

[3] M.J. Kim, Z.H. Chen, P. Majumdar, Finite element modeling of the laser cutting process, J. Comput. Struct. 49 (1993) 231–241.

[4] M.J. Kim, P. Majumdar, A computational model for high energy laser cutting process, Numer. Heat Transfer, Part A 27 (1995) 717–733.

[5] M.J. Kim, Finite element analysis of evaporative cutting with a moving high energy pulsed laser, J. Appl. Math. Model. 25 (2001) 203–22

[6] R.K. Ganesh, W.W. Bowley, R.R. Bellantone, H. Yukap, J. Com-put. Phys. 125 (1996).

[7] R.K. Ganesh, A. Faghri, Y. Hahn, Int. J. Heat Mass Transf. 40(14) (1997).

[8] J.M. Dowden, The Theory of Laser Material Processing (Springer, Berlin, 2009).

[9] Arif AFM, Yilbas BS (2008) Thermal stress developed during laser cutting process: consideration of different materials. Int J Adv Manuf Technol 37:698–704.

[10] Nyon, Mokhtar, Rahman (2012) Finite element analysis of laser inert gas cutting on inconel 718, Int J Adv Manuf Techno 60:995-1007.

[11] Steen WM (1991) Laser material processing. Springer, London, pp 72–80.

ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 3, May 2013
[12] Yilbas BS, Arif AFM (2008) Modeling of residual stresses during laser cutting of small-diameter holes. Proc Instn Mech Engrs Part B: J Eng Manuf 222(12):1577–1587.

[13] Arif, A. F. M. and Yilbas, B. S. Thermal stress developed during laser cutting process: consideration of different materials. Int. J. Adv. Manuf. Technol., 2008, 37, 698–704.

[14] Yilbas BS, Arif AFM, Abdul Aleen BJ (2010) Laser cutting of sharp edge: thermal stress analysis. Opt Laser Technol 48:10–19.

[15] Samant AN, Daniel C, Chand RH, Blue CA, Dahotre NB. Computational approach to photonic drilling of silicon carbide. Int J Adv Manuf Technol 2009; 45:704–13.

[16] Hanon MM, Akman E, Oztoprak BG, Gunes M, Taha ZA, Hajim KI, et al.Experimental and theoretical investigation of the drilling of alumina ceramic using Nd: YAG pulsed laser. Opt Laser Technol 2012; 44:913–22.2012; 212:1257–70.

[17] Ganesh RK, Bowley WW, Bellantone RR, Hahn Y. A model for laser hole drilling in metals. J Comput Phys 1996; 125:161–76.

[18] Dubey AK, Yadava Vinod. Multi-objective optimization of Nd: YAG laser cutting of nickel-based super alloy sheet using orthogonal array with principal component analysis. Opt Lasers Eng 2008; 46:124–32.

[19] Mishra,Yadava. Modeling and optimization of laser percussion drilling of Nickel-based super alloy sheet 2013. Opt Lasers Eng. 2013.