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Numerical Study of Temperature and Stress Fields in Laser Cutting of Aluminium alloy Sheet

Pawan Sharma[a], Avanish Kumar Dubey[b*],Arun Kumar Pandey[c]

[a]*Institute of Engineering & Technology, GLA University,Mathura-281406(U.P),India*
[b]*Motilal Nehru National Institute of Technology Allahabad-211004 (U.P.) India*
[c]*Jaypee University of Engineering and Technology, Raghogarh-473226, Guna (M.P.) India*

Abstract

Due to thermal nature of laser cutting, high temperature and thermal stresses are developed at the cut edge that affects finally the cut edge quality. This paper aims for developing a numerical simulation model to predict the temperature and residual stresses in the laser cutting of Aluminium alloy (Al-2024).The temperature and stress fields developed in cut section are predicted numerically using ANSYS finite element code. For the analysis, Fourier law of heat conduction and Gaussian distribution of a laser beam are considered. Temperature dependent thermo-physical properties of the material are used in numerical simulation. It is found that high temperature gradient exists at laser irradiated spot which results in high thermal stresses across the cut section. Also it has been found that the maximum temperature obtained during laser cutting is reduced with increasing laser scanning velocity. Stress distribution results shows that stresses attains low values at laser irradiated spot because of the reduction of thermal expansion coefficient with increasing temperature. The comparison of results based on numerical simulation with the mathematical model shows good agreements.

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Keywords: Aluminium alloy, Laser Cutting, Temperature and Stress Distribution, Numerical Simulation, Finite Element Method

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* Corresponding author. Tel.: +919336556602; fax: +91-532-2545341.
E-mail address:avanishdubey@yahoo.com, scholarpawansharma@gmail.com, arunpandey76@gmail.com

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Nomenclature

r	Radius of the laser beam (mm)
R	Surface reflectivity
x, y	Distance from centre (0 , 0) of the laser beam in x-and y- direction (m)
I_0	Laser intensity at (0, 0)(W/cm^2)
ρ	Material density (kg/cm^3)
$c(T)$	Specific heat as a function of temperature (J/kg ^0K)
$k(T)$	Thermal conductivity as a function of temperature (W/m-^0K)
Q_{int}	Heat generation rate (W/m^3)
h	Heat transfer coefficient ($W/m^2 \cdot K$)
T_{ext}	External Temperature (293.15 K)
E	Young's modulus
α	Thermal expansion coefficient
ν	Poisson's ratio
$[K]$	Conductivity matrix
$[C]$	Specific heat matrix
$\{T\}$	Vector of nodal temperatures
$\{\dot{T}\}$	Vector of time derivative of $\{T\}$
$\{Q\}$	Nodal heat flow vector
$K(T)$	Temperature-dependent stiffness matrix
$F(t)$	External load vector
$F_{th}(t)$	Temperature load vector
$\{u(t)\}$	Displacement vector

1. Introduction

The precise and complex cuts may not be obtained properly by conventional cutting methods. Laser cutting may be used to fulfill these objectives. Laser cutting of aluminium sheet finds wide applications in industry because of net shaping, low cost, precision of operation, fast processing, and localized machining [Yilbas et al (2013)]. But Aluminium alloys are difficult to cut by a laser, due to their optical and thermal properties such as high reflectivity and thermal conductivity [Pandey and Dubey (2013)].One of the problems arisesin laser cutting of Aluminium alloys is the development of the high temperature gradients near to the cut edges due to their thermal properties that causes formation of high temperature zone and thermal stress in the cut section. And also, the presence of oxygen results in high temperature exothermic reactions taking place in the cutting section that increases the temperature and stresses at the cut section.Inert gasesmay be used to prevent high temperature oxidation reactions at the curt section. The high temperature and thermal stresses developed at the cut section ultimately affect the cut edge quality. Consequently, the analysis of temperature and thermal stress developed at the cut edge becomes necessary.

Pulsed Nd: YAG laser cutting becomes an excellent cutting process because of high laser beam intensity, low mean beam power, good focusing characteristics, and narrow heat affected zone (HAZ) [Dubey and Yadava (2008)]. There has been growing interest in recent years in the use of pulsed Nd: YAG lasers for precision cutting of thin sheet metals and for applications that demand narrow kerf widths and intricate cut profiles. Due to its shorter wavelength (1.06 μm) in comparison to CO_2 (10.6 μm), it is reflected to a lesser extent by metallic surfaces and this high absorptivity of the Nd:YAG laser enables cutting of even highly reflective materials such as aluminium alloy with relatively less power [Mazumdar and Manna (2003)]. Laser Beam Cutting utilizes the high power density provided by the laser beam, which is focused on the work piece.Also the cutting speed and pulse width have been found the significant control factors in laser cutting of difficult-to-laser-cut Al-alloy [Norkey et al (2013)].As a result, the work piece material experiences heating, melting, and possible vaporization and re-solidification. Understanding the temporal evolution of the temperature field during laser material interaction is one of the most significant factors in achieving a desired quality of processing.

Many theoretical studies have been conducted for determining the temperature and stress field distribution in laser cutting of different materials. Anthony et al. (1977) did the first quantitative work and proposed the theory and mathematical model for the laser heating and melting with Gaussian power distribution and a constant moving heat source. They co-related the cooling rate distribution and the depth of the melting with the size, velocity and power level of the spot. Chan et al. (1984) considered a two-dimensional transient model of laser melting where the movement of the heat source was taken into consideration by coordinate transformation. Yilbas et al. (2012) have investigated laser straight cutting of zirconia tiles using finite element codes. Their model has shown that the temperature variation along the work piece thickness is gradual resulting in a small temperature difference between the top and bottom surface along the cutting edge. Von Mises stress attains high values in the region near the cutting edge.Sheng and Joshi (1995) have developed a numerical model to estimate heat affected zone (HAZ) in laser cutting of stainless steel. Nyon et al. (2012) have simulated the laser inert gas cutting of Inconel 718 and concluded that the temperature rises sharply in the region close to the laser heat source.

Yilbas et al. (2013) used FEM to predict temperature and stress fields during the laser cutting of 5 mm thick mild steel sheet by neglecting the reflection of laser beam from cut edge surface and moving heat source. It was found that temperature remains high at the sharp edge when the laser beam was located in this region. They also found the residual stress of 90 MPa at the sharp corners and maximum von Mises stress of 280 MPa, away from the sharp corners. Nisar et al. (2010 a) developed 3-D transition model to determine the temperature distribution, which was further used as an input to find thermal stress during the diode chip-free laser cutting of glass sheet. Qin et al. (2010) developed an axisymmetric mathematical model to predict temperature and thermal stress for the long pulsed Nd:YAG laser heating of 2024 Aluminium alloy sheet by considering Gaussian mode laser beam. The results indicated that the plastic damage occurs in the top layer of the plate, where the residual radial stress was tensile and could even reach 250MPa, approximately. Nisar et al. (2010 b) applied FEM to simulate the transient effects of the moving beam and predict thermal fields and stress distributions. It was shown that an increase in the thickness of the glass sheet for the same power and cutting speed or an increase in the cutting speed with constant power and a given sheet thickness results in smaller cut path deviations at the leading and trailing edges of the glass sheet.

Yi et al. (2011) developed 3-D transient model in ambient dry air, and water using FEM by considering thermo-mechanical parameters which depend on temperature and moving heat source. Based on the proposed models, the transient temperature fields and residual stress distributions on workpieces were investigated. The numerical results suggested that the states of temperature and residual stress fields could be improved to different degrees using water film and water ambient. Melhem et al. (2011) developed 3-D mathematical model to analyze the flow field in the kerf and its surrounding, and heat transfer rates from the kerf wall using the control volume approach. They found that jet expansion from the nozzle accelerates the flow and the presence of the kerf reduces the flow acceleration at the kerf inlet. The thermal stresses developed in the cutting section, had been modeled by Yilbas et al. (2011) using finite element software ABAQUS. They found that the high conductivity of bronze increases the cooling rates within the cutting section, which influences the thermal stress field in the cutting region. The residual stress predicted was in order of 200 MPa within the vicinity of the hole circumference. Hu et al. (2011) developed 3-D axial symmetrical model of laser cutting and further applied FEM based numerical simulation to investigate the flow field of shield gas in cutting slots. Scintilla and Tricarico (2012) developed 3-D semi stationary thermal model to predict average cutting temperature in HAZ and conduction losses for inert gas fusion cutting of 1, 5, and 8 mm thick 90MnCrV8 sheet. Model was validated by experimental data. The conduction losses estimation was used for justifying the lower quality of disk laser cuts due to the lower average cut front temperature. A good agreement was found for all the test cases considered.

Yan et al. (2013) developed 3-D finite element model to simulate temperature field and thermal stress distribution for crack-free laser cutting of thick-section alumina. They found that the sufficient cooling effect during laser-off periods was crucial to develop a low thermal-stress distribution during laser cutting, by which the crack-free cutting could be achieved. Shuja and Yilbas (2013) used FEM to predict the temperature and stress distribution in the irradiated region by assuming laser scanning speed constant and thermal properties are temperature dependent. It was found that two temperature peaks were formed along the x-axis. The first temperature peak had higher value than the second peak. List et al. (2013) developed a stream line model to investigate the distribution of velocity during the very high speed laser cutting of mild steel sheet. A FEM based on a Lagrangian formulation had been used to corroborate the conclusion of the streamline model and it was found that the simulation results were similar to the experimental observations with regards to the magnitude of the equivalent strain rate and cumulative plastic strain but slightly differ in the geometry of flow pattern.

The review of literature shows that most of the theoretical studies are based on numerical solution. The researchers have made different assumptions related to the material properties but the mode of heat transfer is limited to conduction only. The effect of convective as well as radiative heat transfer has not been considered. In their studies, researchers have considered homogeneous and isotropic characteristics of material. Also, rarely any researcher has incorporated the effect of reflectivity/absorptivity of materials during their analysis. Only few papers have been found related to the numerical simulation of laser cutting of Aluminium alloy sheet. The objective of this study is to develop a finite element based computational model using ANSYS finite element code to determine the spatial temperature distribution history and residual stresses by incorporating reflectivity/absorptivity of Aluminium alloys. The model is based on a transient heat transfer equation along with heat losses by convection. Also the effect of changes in velocity and peak power intensities on the temperature distribution is shown utilizing the finite element based model.

2. Theory and Mathematical Formulation

As the laser beam is focused on the work piece, 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. Following assumptions have been made in the analysis of the laser cutting;

1. The material is isotropic and opaque.
2. The spatial distribution of the laser beam is in Gaussian at TEM_{00} mode.
3. Effect of vaporization is ignored as the molten material is removed immediately from the work piece by an assist gas pressure.
4. The thermal history of the heat affected zone is determined by the effects of conduction and convection only, i.e. the effects of radiation are ignored. Moreover, the coefficient of convection between the work piece and the environment is assumed to be a constant.
5. Effect of cooling due to assisting gas is ignored.

2.1 Modeling of Heat Source

Modeling heat source is the most important part in the analysis of laser cutting process. 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. 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 [Bahotre and Harimkar (2008)]. The Gaussian profile of laser beam is shown in Fig. 1. The laser beam intensity which is incident on the surface of the material is given by the expression as follows:

$$I_{(x,y,z,t)} = (1-R)\, I_0 \exp^{(-a.z)} \exp\left[-\frac{(x^2+y^2)}{r^2}\right] \tag{1}$$

2.2 Heat Transfer Analysis

Heat Transfer in the laser cutting process is modeled as two dimensional transient analyses. The spatial and temporal temperature distribution T(x, y, t) satisfies the following differential equation for two-dimensional heat conduction in a domain D [Sowdari and Majumdar (2010)]. Governing equation for the model is based on basic Fourier law of heat conduction and is described as;

$$\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[k(T)\frac{\partial T}{\partial y}\right] + Q_{int} = \rho c(T)\frac{\partial T}{\partial t} \tag{2}$$

Table1 Laser cutting parameters selected for analysis [Dubey et al. (2012)]

Parameters	Numerical values
Laser Power (kW)	2
Absorption coefficient (1/cm)	0.15
Beam radius (mm)	0.1×10^{-3}
Convective heat transfer coefficient (W/m^{2}K)	20
Pulse duration (ms)	1.2
Pulse frequency (Hz)	28

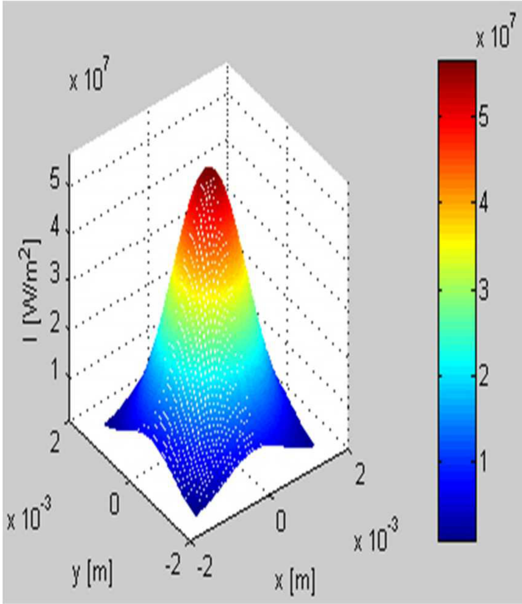


Fig 1: Gaussian distribution of laser beam

To solve the above governing equation, the boundary and initial conditions are as follows;

1. The initial condition :

$$T(x, y, 0) = T_0 \text{ for } (x, y) \in D \quad (3)$$

The essential boundary condition: $T(0, y, t) = T$ (4)

on the boundary S_1 *for (0,y)* $\in S_1$ and $t > 0$. This condition prescribes nodal temperatures at the flow inlet. S_1 represents the inlet surface.

2. The natural boundary condition **:** $q_0 = h.(T_{ext} - T)$ (5)

on the boundary S_2 for $(x,y) \in S_2$ and $t > 0$. S_2 represents those surfaces that are subject to convection and imposed heat fluxes.

2.3Thermal Stress Analysis

As the laser beam moves along the surface of the aluminium alloy sheet, the heated zone cools down due to radial heat conduction and convection from the surfaces, thus thermal stress are developed due to the rapid cooling. The thermal stress caused by the temperature difference ΔT is written as:

$$\sigma_{thermal} = \frac{E \alpha \Delta T}{1 - \nu} \quad (6)$$

Also, equivalent von-misses stress is given by the following relation as:

$$\sigma_m = \sqrt{\left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}\right]} \quad (7)$$

Where, $\sigma_1, \sigma_2, \sigma_3$ are the three principal stresses from any point in the x, y, or z directions of the principal axis.

3. Finite Element Formulations

In the analysis, temperature dependent thermal and mechanical properties have been considered and cutting parameters used are shown in the Table 1. Mathematical solutions are also obtained using MATLAB codes. Flow chart for the simulation process is shown in fig. 2(a). Global equation for thermal analysis is obtained using finite element formulation as:

$$[C(T)]\{\dot{T}\} + [K(T)]\{T\} + \{V\} = \{Q(T)\} \quad (8)$$

Global equation for mechanical analysis is obtained using finite element formulation as:

$$\left[K\left(T\right)\right]\left\{u\left(t\right)\right\}+\left\{F\left(t\right)\right\}+\left\{F_{th}\left(t\right)\right\}=0 \tag{9}$$

3.1 Finite Element Simulation

Finite element simulations have been performed using the cutting parameters shown in Table 1. The laser beam travels along the x-axis, (i.e., the symmetrical axis of the aluminium alloy work piece); also only half of the work piece is modelled in order to reduce the computational time. The effect of mechanical deformation on heat flow during laser cutting has been considered insignificant as it is negligible.

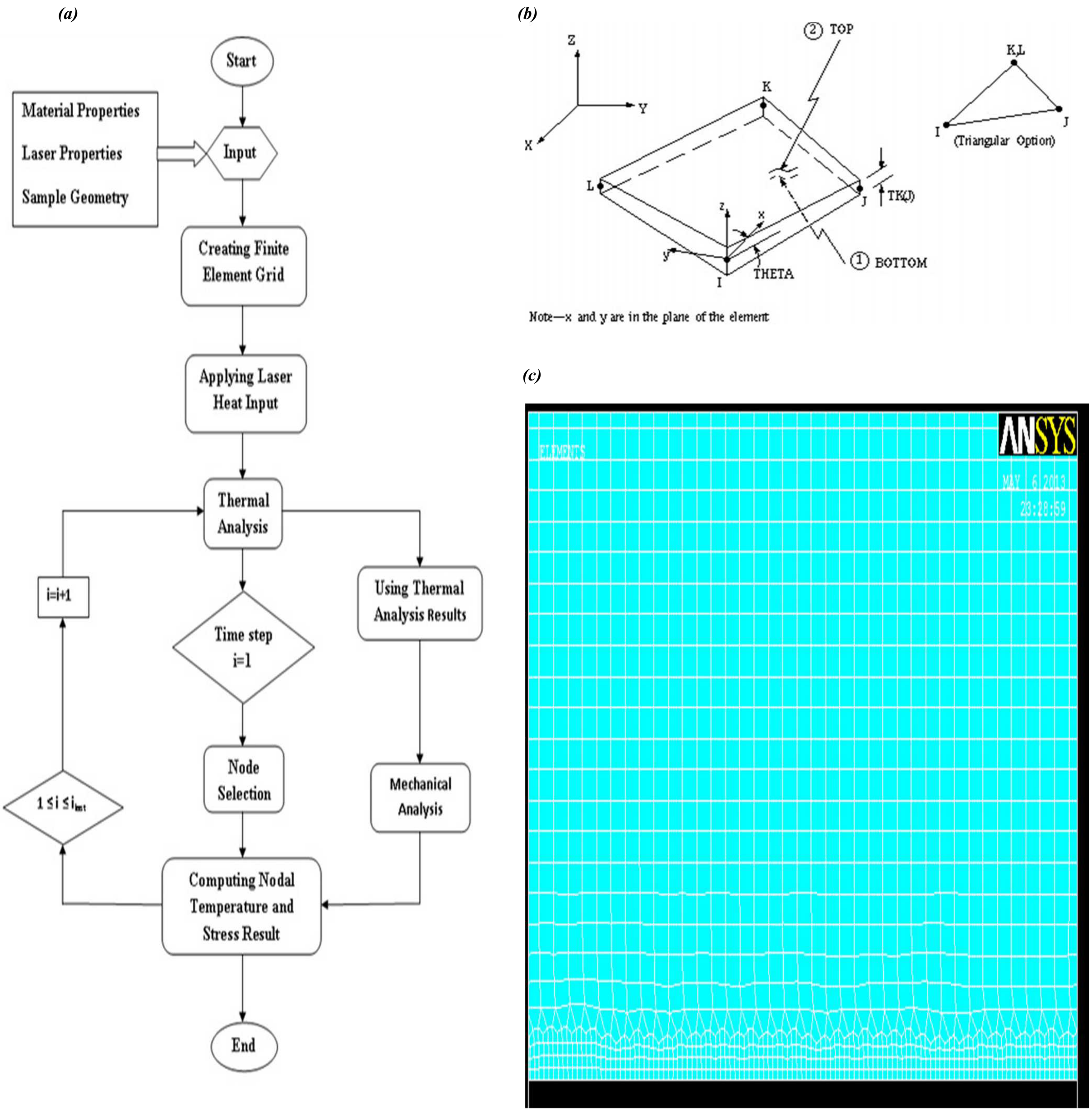


Fig. 2 (a) Flow Chart for Simulation; (b)SHELL 57 Element[ANSYS 2009];(c) 2-D Finite Element Geometry and Mesh

Therefore, a sequentially coupled physics analysis using ANSYS has performed to determine the temperature distribution and the resulting thermal stress in the work piece. The outputs of the thermal analysis are treated as input for the mechanical analysis using ANSYS Parameter Design Language (APDL) programming language. Both analyses have been performed with the same mesh but different element types.

3.2 Mesh Generation

Thermal element SHELL57 [ANSYS, 2009] is used in the transient thermal analysis, whereas an equivalent structural element SHELL41 [ANSYS, 2009] is adopted in the mechanical analysis. A detailed description of the elements and the mesh are shown in the fig.2 (b) & fig.2(c).

4. Results and Discussion

The numerical simulation has been used for reliable prediction of temperature and stress distribution to the Nd:YAG pulsed laser cutting of an aluminum alloy using the cutting parameters as shown in Table 1. Table 2 shows the thermo mechanical properties for an aluminium alloy 2024 used in the simulation.

Table 2 (a) Thermal properties of Aluminium Alloy 2024

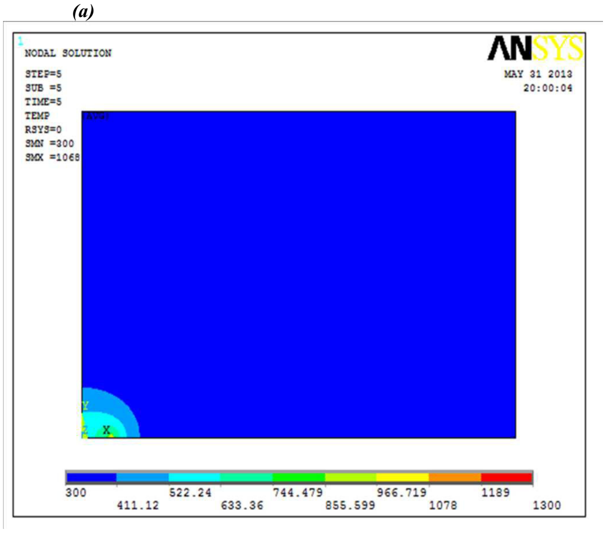
Temp. (°C)	Thermal Conductivity (W/m °C)	Specific Heat (J/Kg °C)	Density (Kg/m³)
0	100	896	2823
100	140	915	2754
200	160	950	2705
300	155	952	2654
400	145	1080	2613
500	145	-	2559
600	180	-	2500
700	238	-	2485
800	238	-	2485

(b) Mechanical Properties of Aluminium Alloy 2024

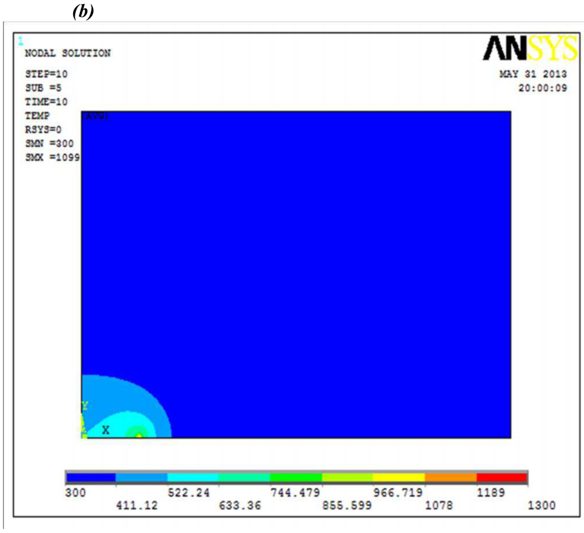
Temp. (°C)	Elasticity Modulus (N/mm²)	Expansion
0	-	2.24E-05
24	72.39E+03	-
100	70.33E+03	-
200	-	2.37E-05
204	62.34E+03	-
232	60.67E+03	-
260	58.61E+03	-
288	55.16E+03	-
300	-	2.46E-05
316	52.40E+03	-
371	43.44E+03	-
550	5.000E+03	-

4.1 Temperature Distribution

(a)



(b)



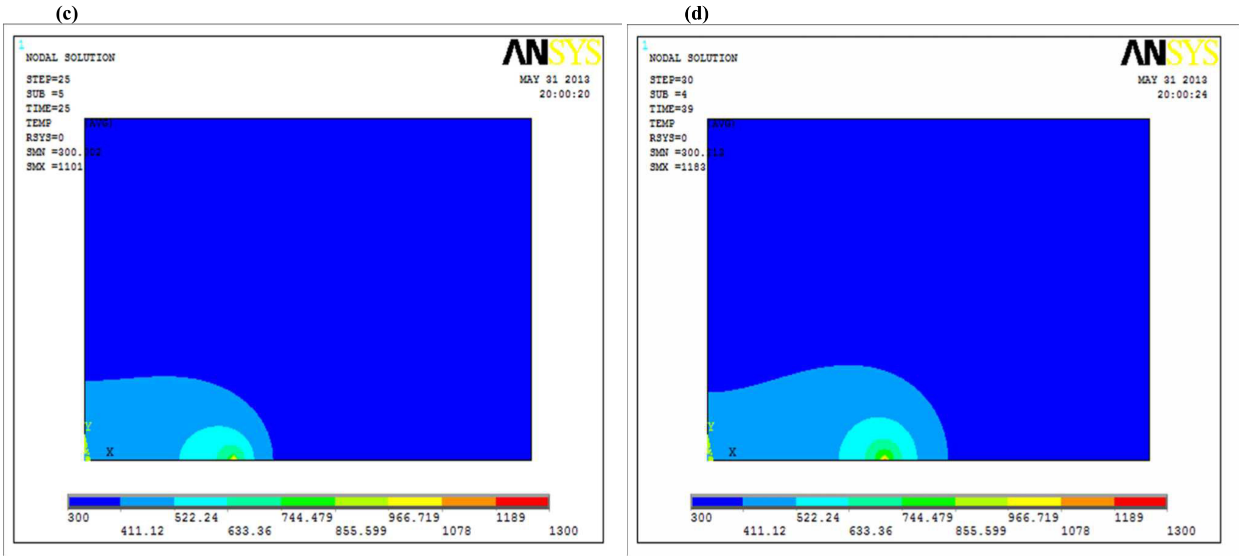


Fig. 3: Temperature Distribution along cutting edge at :(a) t=5sec; (b) t=10sec; (c) t=25sec; (d) t=40sec.

It can be seen from the fig.3 that the maximum temperature is obtained at the centre of focusing spot on the workpiece. As the distance from this point increases, the temperature on the surface decreases. At the focused spot, the temperature reaches to the melting temperature of material. This is particularly true in the region of the laser irradiated spot where the laser intensity is maximum. Consequently, temperature difference between the laser irradiated spot and its frontal neighbourhood becomes considerably large. It should be noted that the laser beam moves at a constant speed along the plate surface during the cutting process; therefore, the frontal region of the laser irradiated spot corresponds to a region prior to cutting (i.e uncut material), which is at the initial temperature. As the laser beam is focused on a spot of the work piece, temperature at its frontal region is also increased because of the conduction of the heat along the surface of the aluminium alloy plate. However, as the cutting progresses temperature behind the laser irradiated spot along the surface is reduced. This is because of the high thermal conductivity of aluminium alloy, which increases the heat conduction from the heated region to the solid bulk. Also the thermal conductivity of the aluminium alloy increases with the temperature as depicted in Table 2; thus resulting in high thermal gradient at the surface of work piece.

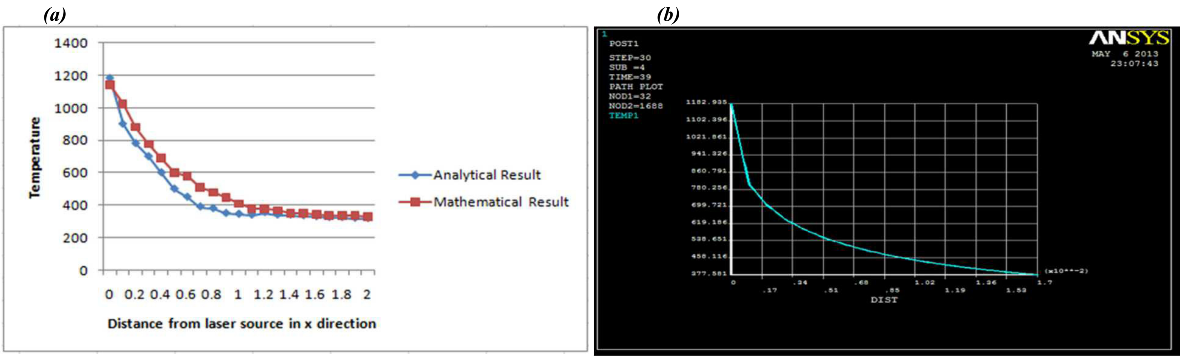


Fig. 4(a) Comparison of analytical result with mathematical result of Temperature Distribution ;(b) Time-Temperature Distribution.

Again it is evident from fig. 4 that the thermal gradient obtained at the surface of the aluminium alloy plate is high which results in high thermal stresses. Also time-temperature plot for the laser beam cutting of aluminium alloy has been shown in the fig. 4. Heating and cooling cycle are shown in the plot, it can be seen that the temperature increases to a maximum at initial time step this is the time when the laser beam is focused on a spot on the aluminium alloy work piece representing the heating cycle and as laser beam propagates along the surface at the location behind irradiated spot, temperature starts reducing thus representing the cooling cycle.

4.2 Effect of Laser Scanning Velocity on Temperature Distribution

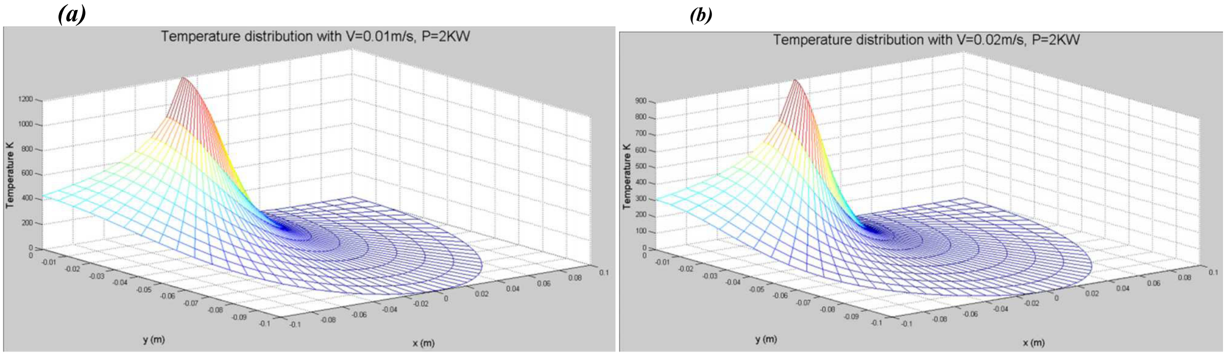


Fig. 5 Temperature Distribution at different scanning velocity: (a) 0.01m/s ; (b) 0.02m/s.

As it is evident from the fig. 5, that as the scanning velocity during the laser cutting is increased, the maximum temperature is reduced from 1200K at v=0.01m/s to 600K at v=0.02m/s i.e. almost half reduction. Also changes in velocity affect the temperature distribution along the surface. This may be due to less amount of laser energy absorption on the surface of aluminium alloy as the time for laser material interaction is reduced and also the high reflectivity of aluminium surface causes further reduction in temperature

4.3 Stress Distribution

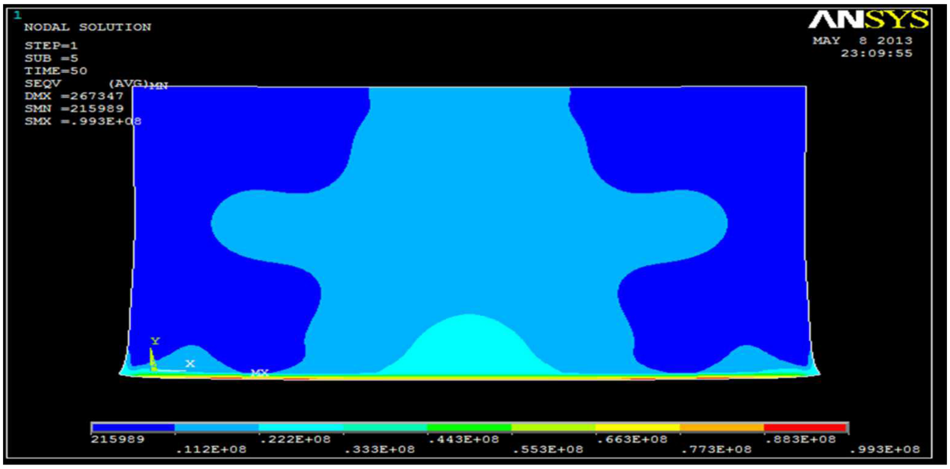


Fig. 6 Von Mises stress distribution

Fig. 6 shows the Von Mises stress distribution along the surface of the plate at a particular time step.It is evident that the Von Mises stress contours attain significantly high values at locations where the laser beam is focused along edge. As edges are not free to expand, high thermal strain is obtained at the edges which finally results high thermal stresses. However, von Mises stress attains low values across the laser irradiated spot. As thermal expansion coefficient is the function of temperature and it reduces by increasing the temperature, that’s why the stresses attains low values where temperature is high i.e. at laser irradiated spot. This reduction in von Mises stress is associated with an attainment of reduced elastic modulus at high temperatures shown in Table 2.

5. Conclusions

A finite element model for laser cutting of an aluminium 2024 alloy has been developed using ANSYS finite element software package and MATLAB. A coupled numerical solution algorithm has also been developed to compute the temperature and residual stress distribution along the cutting edge in the surface of the material. The numerical simulation results show that the temperature rises sharply in the region close to the laser heat source. However, the temperature gradient reduces sharply and gradually when the distance increases from the cutting edge. In addition, high temperature gradient in the cutting edge causes, low coefficient of thermal expansion i.e. low thermal stresses. Also the affect of cutting velocity on temperature distribution has been shown which provides satisfactory details for the appropriate cutting speed for efficient laser cutting of aluminium alloy. Analytical results obtained shows good agreement with the mathematical results.

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