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SIMULATION OF ND: YAG PULSED LASER NUMERICALLY TO ESTIMATE THE EFFECT OF LASER BEAM ON THE QUALITY OF CUT ZONE FOR ALUMINUM ALLOY 2024-T3

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Abstract

This work presents a study about using the Finite Element Methodology (FEM) represented by ANSYS software for simulation Nd: YAG pulsed laser cutting technology in the machining of airplane structure pieces. A three-dimensional workpiece of (20 mm × 16.5 mm × 0.5 mm) is modelled by SOLIDWORKS software and the mesh resolution is adopted to check if the numerical results are affected by a number of elements. The simulation process includes coupling of a transient thermal model with the static structural model. The laser power beam is modelled as heat flow load moving along the workpiece and the temperature-stress fields with respect to time has been analysed. The temperature distribution for moving high power source is evaluated at the scanning line "cut edge". Two laser powers are adopted namely; 150 W and 200 W to study its effect on the process quality. The results show the ability of Finite Element Method to predict temperature distribution at cutting zone, thermal and mechanical stresses, and cutting forces accurately.

Keywords: Aluminium alloy 2024-T3, Cut edges, Finite element method (FEM); Laser cutting technology; Nd: YAG pulsed laser.

1. Introduction

A laser is a device used for amplifying of electromagnetic radiation to produce high power beam focusing into a small point. Laser's technology has been used in many industrial applications including marking, welding, and cutting materials due to its unique characteristics of being highly accurate technique and cost competitive [1]. Unlike conventional cutting tools, Laser cutting machines are well known of being ultra-flexible with high quality products. In this respect, optimal laser power may require over cutting complicated paths [2]. Laser techniques have an obvious effect in solving industrial problems such as cutting thick edges with high accuracy using Taguchi [3], and also using a laser in the manufacturing processes by means of ablation mechanism known as laser ablation [4].

The importance of laser has been engaged with the artificial neural network (ANN) to predict the quality of depth of micro-grooving manufacturing process [5]. The laser demonstrates its importance in the lathing process by forming the materials stock into desired cylindrical shapes [6]. Laser technique plays a crucial role in predicting surface roughness, Networked Fuzzy Intelligent System (N-FIS) combined with commercial software to predict the roughness values of material surfaces [7]. Laser cutting technology type pulsed Nd:YAG is considered as an excellent cutting technique due to its high accuracy, Pulsed Nd:YAG laser is intensively used in cutting thin metal sheets since it has short wavelength of 1.06 μm over 10.6 μm of carbon dioxide CO_2. Materials such as aluminium alloy has been reported with high reflectivity and thermal conductivity, so it would seem quite hard to cut by laser beam [8]. Thus, Nd:YAG laser beams is qualified for cutting highly reflective materials such as aluminium alloy with relatively less power intensity [9, 10].

Multiple factors have been examined to investigate the quality and precision of cutting edge, the cutting-speed and pulse-width deem in laser cutting technology for processing highly reflective alloys such as aluminium alloy [10]. The intensity of temperature gradient and thermal stress of aluminium alloy was predicted following anew developed numerical model. Finite element technique was used as a tool to facilitate simulation through ANSYS software. Fourier law and Gaussian equation were implemented to solve heat conduction and laser beam power. Authors reported a remarkable reduction in cutting optimal temperature over increased laser scanning velocity. their results were in good agreement with previously reported mathematical models [11]. In another study, the thermo-mechanical stresses in heat affected zone of stainless-steel square blanks was examined and investigated. The results revealed that the rate of temperature variation was dramatically affected by cutting speed. They also emphasized the fact that the heat influenced zone width is proportional to laser power [12].

Therefore, the amount of heat generated during the cutting process may has a negative impact on the cutting process that ultimately downgrades the product quality including cutting edge and surface integrity. Such difficulty could be vanished over adequate study of the heat profile associated with cutting process. [13]. Numerical calculations were implemented in order to estimate the effect of laser beam on the quality of cutting zone shape thereby examining those parameters influencing the cutting process [14]. It has been reported that complicated shapes of different metallic surface sheets were successfully processed following CO_2 laser cutting technology. Titanium alloy Ti-6Al-4v was used to examine the impact of such technology on kerf quality. Authors reported that non-uniform Kerf width was obtained over CO_2 laser technique [15].

An attempt to predict the thermal stress and formation of kerf width during the laser cutting operation was performed using Finite element method represented by ANSYS software to develop a numerical model of cutting Inconel 718 within laser inert gas, Gaussian model was used for simulation of laser beam, laser power beam as continuous wave where the influence of cutting speed and laser intensity on kerf width was examined. Numerical analysis were in geed match with experimentally obtained data [16]. A numerical heat transfer model with three dimensions to simulate the laser structuring polymer material was investigated and developed using ANSYS Parametric Design Language (APDL), APDL was adopted to study and analyse the laser speed and laser power and also to investigate the depth and width of the grooves, Gaussian distribution model was used for modelling of laser as heat source, the effect of convection and radiation heat transfer was considered within the analysis, the results liberate laser scan speed and laser power as the most influential factors that affect the quality of laser structure process, Authors reported that high speed laser and moderate power would produce an optimal cutting quality [17]. A numerical investigation was performed to study the effect of mesh dependency on the accuracy of numerical results [18]. The study included three types of mesh differs in number of elements. In similar attempt the authors used unstructured mesh for simulation requirements to investigate the accuracy of resulted numerical data and computational time throughout the simulation process [19].

In the literature, there are considerable data regarding conductive heat transfer in analytical models. However, convention and radiation heat transfer phases are yet engaged. In addition, material absorptivity and reflectivity are yet incorporated. In this respect, current study aims to numerically examine the impacts of convention and radiation heat transfer on the thermal distribution and residual stresses of the cutting edge of 2024-T3 Aluminium alloy. It also examines the effect of laser power intensity on the residual stress and temperature distribution of the cutting edge.

2. Theory and Mathematical Model of Laser Cutting Process

When high power laser beam is concentrated on the workpiece, the workpiece material will absorb some of this energy and reflect the rest. The absorbed portion of laser energy is conducted into workpiece material and then lost by convention effect from the surface of the material. The effectiveness of absorbing laser energy by the material is governed by many factors including; optical and thermal properties, laser beam wavelength, polarization and workpiece material. Therefore, the used material was assumed to opaque and isotropic. The following assumptions were made in the analysis of laser cutting process;

- The laser beam distribution introduced according to Gaussian mode.
- Vaporization effect is negligible, the assist gas pressure used for removing the molten material immediately from the workpiece.
- Convection and conduction heat transfer are used for predicting the thermal history of the heat affected zone, and the convection heat transfer coefficient between environment and workpiece is assumed to be constant.
- The cooling effect of assistant gas is ignored.

2.1. Modelling of geometry "workpiece"

Modelling of workpiece was performed by using of SOLIDWORKS program. This is mainly due to the fact that SOLIDWORKS program provides the accuracy, flexibility of work and the ability to accomplish complex shapes smoothly. A cuboid with dimensions 20 mm length, 16.5 mm width, and 2 mm height was adopted and modelled as the workpiece, as shown in Fig. 1. The modelling process included specialization of scanning zone by generating tiny cuboids (2 mm length ×0.5 mm width × 2 mm high) along scanning axis as simulation requirements and for adjusting the mesh in the scanning area. The mechanical properties of 2024-T3 Aluminium alloy are given in Table 1

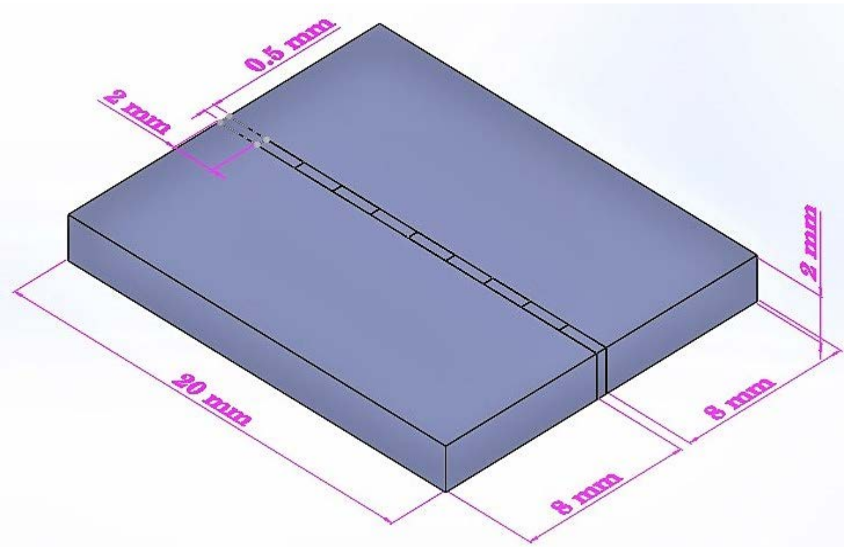

Fig. 1. Three-dimensional model of workpiece.

Table 1. Aluminum alloy 2024-T3 mechanical properties.

Parameters	Numerical values	Unit
Density	2768	kg/m^3
Modulus of Elasticity	1034.2	kPa
Poisson's Ratio	0.33	-
Yield Stress	0.275	GPa

2.2. Mesh generation

Mesh used for dividing the computational domain to finite elements to make the analysing process easier and more accurate. In the present work, a structured grid with hexahedral element has been adopted. The better convergence and high resolution are the most significant characteristics that distinction structured grid over unstructured type. For obtaining good and accurate numerical results, a refining technique was adopted in the scanning area exposed to the laser heat flow, as shown in Fig. 2.

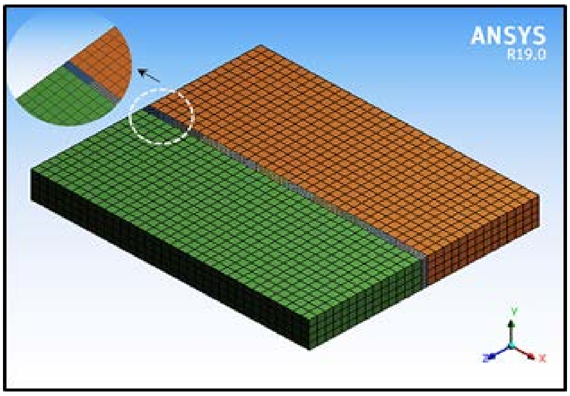

Fig. 2. Three-dimensional model of workpiece after meshing process.

Mesh dependency technique was used to check if the numerical results were affected by a number of elements. Through taking maximum temperature into account as a mesh dependency criterion and tested for three types of mesh differs in the number of elements which are “coarse, medium and fine” mesh, as illustrated in Table 2. Medium mesh type was used and adopted for all cases due to its acceptable accuracy, where error percentage equal to 0.4% compared with a fine mesh type as it intended to expand computational time.

Table 2. Mesh dependency criterion data.

Mesh type	Number of elements	Maximum temperature °C
Coarse	183,900	8498.4
Medium	480,200	8304.9
Fine	620,315	8270.8

3. Modelling Laser as a Heat Source

Modelling of a laser as a heat source considers the most significant part in the analysis of laser cutting technology. Beam shaping method view different kinds of beam shapes including rectangular, circular, Gaussian, etc. the distribution of Gaussian energy consider the preferred mode for simulating the laser cutting technique. This is mainly due to the ability of controlling the beam diameter of laser for the purpose of energy concentration and cutting by generating high power beam [20].

The intensity of the laser beam that is incident on the material surface can be expressed according to the following equation [11].

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

3.1. Heat transfer analysis

The simulation of heat transfer phenomena in the laser cutting process was performed following two-dimensional transient. The differential equation for heat conduction with two dimensions in the domain can be satisfied with spatial and temporal temperature distribution $T_{(x,y,t)}$ [21]. The governing equation for heat conduction model based on Fourier law can be described below.

$$\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(T)\frac{\partial T}{\partial y}\right]+Q\,\frac{\partial T}{\partial t}_{int} \quad (2)$$

3.2. Boundary and initial conditions

It is essential to specify the boundary and initial conditions of the domain so as to the flow variables on physical field boundaries is readily specified. To solve the governing equations, the boundary and initial conditions should be set as follows;

According to initial conditions:-

- $T_{(x,\,y,\,0)} = T_0$ for $(x,y) \in D$
- $T_{(0,y,t)} = T$
- $S_1$for $(0,y) \in S_1$ when $t > 0$, (this condition describe nodal temperatures at flow inlet section, where S_1 symbolizes the inlet surface).

According to boundary conditions:-

- $Q_0 = h.(T_{ex} - T)$
- S_2 for $(x,y) \in S_2$ when $t > 0$, (where S_2 symbolizes the surfaces that are exposed to convection and heat fluxes).

3.3. Thermal stresses analysis

When laser beam transfer over the aluminium alloy surface sheet generates what called heat scanning zone due to the high power of the laser. Such heat zone will eventually cool down due to the radial conduction and convection action being taking place. As a result, thermal stresses will occur.

The thermal stresses resulting from temperature difference ΔT can be written as follows:-

$$\sigma_{thermal} = \frac{Ea\Delta T}{1-\nu} \quad (3)$$

The equivalent stress of Von-misses can be found according to the following equation

$$\sigma_m = \sqrt{\frac{(\sigma_1-\sigma_2)+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \quad (4)$$

where σ_1, σ_2, σ_3 are the principal stresses for any point in three-dimensional axis (x, y, z).

3.4. Finite element formulation

For analysing purposes of laser cutting process, the temperature is considered as dependent factor affect both thermal and mechanical properties. Parameters including laser power, absorption coefficient, beam radius etc. used are listed in Table 3.

The thermal analysis equations can be obtained using the formulation of finite elements [11]:-

$$[C(T)]\{\dot{T}\} + [K(T)]\{T\} + \{V\} = \{Q(T)\} \quad (5)$$

The mechanical analysis equation can be obtained using the formulation of finite element as:-

$$[K(T)]\{u(t)\} + \{F(T)\} + \{F_{th}(t)\} = 0 \quad (6)$$

Table 3. Laser cutting parameters selected for analysis.

Parameters	Numerical values	Unit
Laser power	150 and 200	W
Absorption coefficient	0.15	1/cm
Beam radius	0.5	mm
Convection heat transfer coefficient	20	W/m2K
Pulse duration	2	ms
Pulse frequency	28	Hz

4. Simulation Process

According to the cutting parameters listed in Table 3, the simulation process was performed, as shown in Fig. 3. The laser beam moves forward along symmetrical axis “X-axis” of the aluminium alloy workpiece. In this present study, the mechanical deformation provided from laser cutting heat flow was assumed negligible.

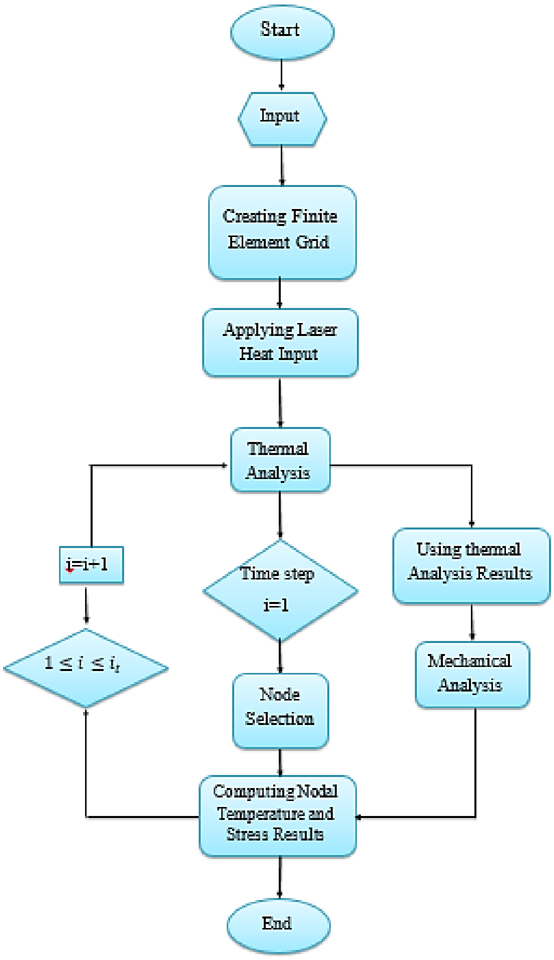

Fig. 3. Flow chart illustrates the simulation process.

To investigate temperature distribution and resulting thermal stress, an analysis including coupled physics was performed thereby using ANSYS software. The output data resulting from thermal analysis are used as input data for the mechanical analysis using APDL programming language "ANSYS Parameter Design Language.

5. Results and Discussion

A numerical analysis has been performed to simulate the Nd: YAG pulsed laser cutting technique and predicting the thermal and mechanical stress loads of an aluminium alloy 2024-T3 using the cutting specifications listed in Table 3.

5.1. Temperature distribution

Figures 4 and 5 illustrate the temperature distribution contours after pass 1- and 10-seconds heat duration respectively. The irradiated line of laser match to the straight line when *y*=0, the maximum heating loads are constantly at this straight line during the heating process.

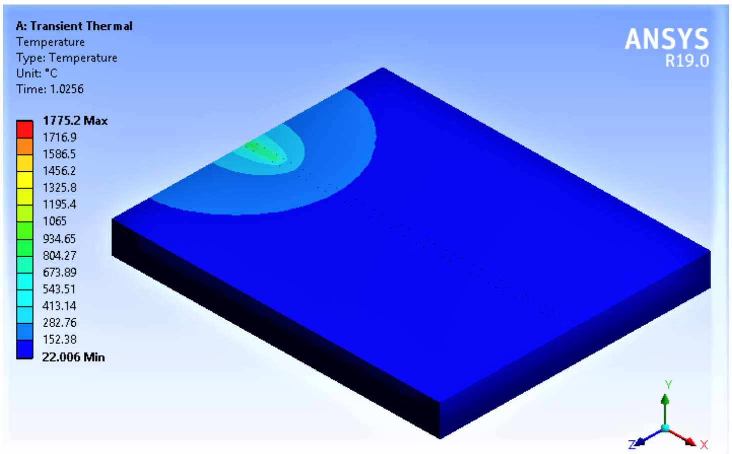

Fig. 4. Temperature distribution contour at t=1 s.

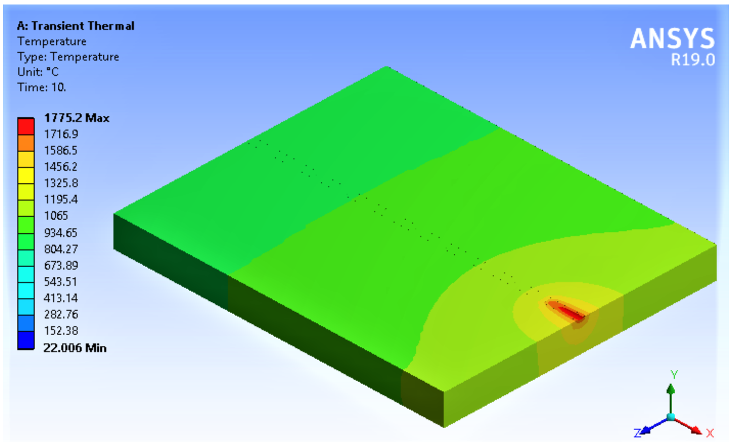

Fig. 5. Temperature distribution contour at t=10 s.

It should be noticed from the above figures that the maximum value of temperature can be recognized at the centre of the laser focused spot on the workpiece. At the laser centre spot, the temperature reaches its optimal value "melting temperature" of material due to the maximum intensity of laser located at the centre of the beam. This will be resulted in remarkable temperature difference between point temperature positioned in the centre of the beam and frontal neighbourhood points. The preheating operation resulting from conduction of heat between focusing spot and frontal region along the surface of the workpiece [1], as well as constant scanning speed of the laser will promote good and smooth cutting process.

Figures 6 and 7 display a longitudinal cross section contours of temperature distribution of 2024-T3 aluminium alloy workpiece. It would seem that the temperature behind the laser beam spot along the surface is increased as cutting processed which is believed to be due to the high thermal conductivity of aluminium alloy.

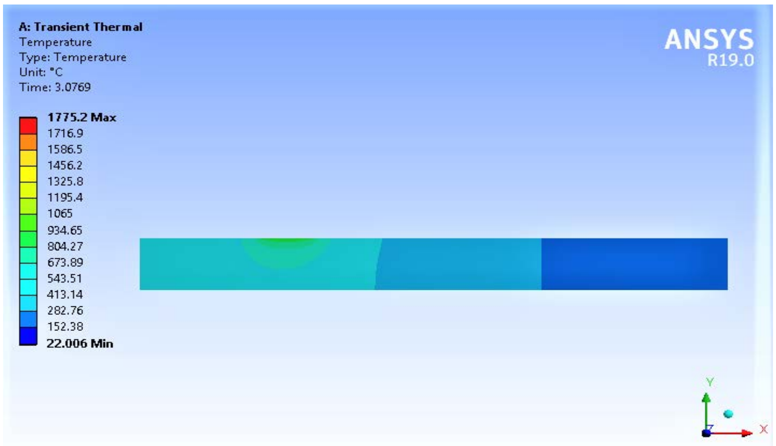

Fig. 6. Longitudinal cross-section contour of temperature distribution at *t*=3 s.

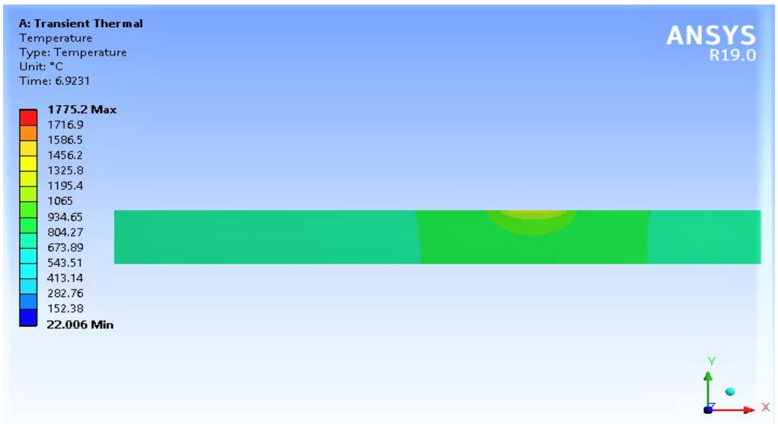

Fig. 7. Longitudinal cross-section contour of temperature distribution at *t*=7 s.

As a result, the heat of conduction will increase from heated region to the solid bulk. Since aluminium thermal conductivity is proportional to its temperature [11], causing high-thermal gradients at the surface of workpiece.

Figures 8 and 9 display the temperature distribution contours of workpiece beyond 10 seconds at different laser power 150 W and 200 W respectively.

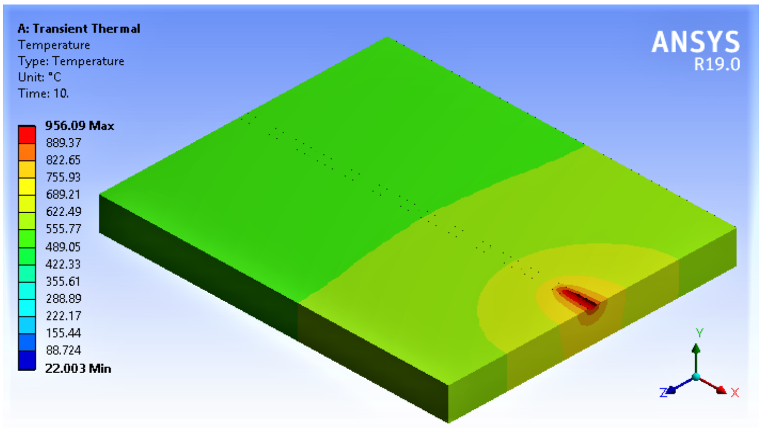

Fig. 8. Temperature distribution contour at *t*=10 sec and laser power 150 W.

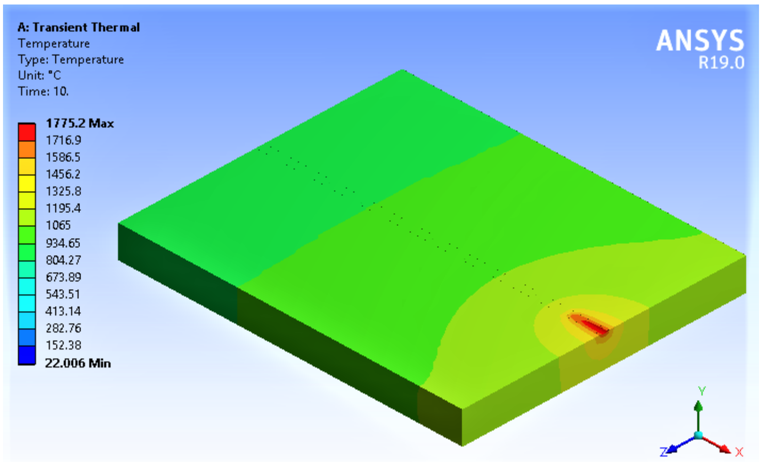

Fig. 9. Temperature distribution contour at *t*=10 sec and laser power 200 W.

Obviously from the figures, a uniform distribution of temperature can be found. However, the optimal value of temperature in the laser heating spot increases with an increased power [12].

5.2. Stress distribution

Figures 10 and 11 show distribution contours of Von Mises-stress along the surface of the workpiece at a certain time step and for two laser power sources. Both Figures indicate that the regions located along the scanning line of the workpiece surface where they affected by the focused laser beam achieved high values of von Mises stress.

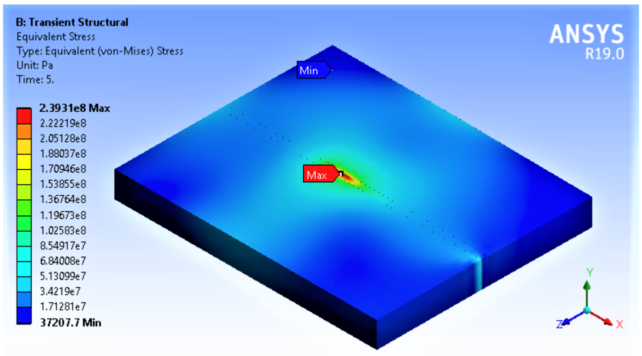

Fig. 10. Distribution contour of equivalent (Von-Mises) stress at *t*=5 sec and laser power 150 W.

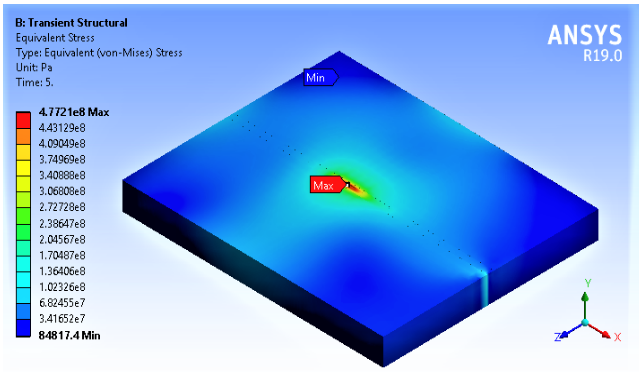

Fig. 11. Distribution contour of equivalent (Von-Mises) stress at *t*=5 sec and laser power 200 W.

It should be mentioned that as laser power rises from 150 W to 200 W, von-Mises stress value increases within regions located at laser irradiation spot due to the effect of thermal stress.

Figures 12 and 13 show the distribution contour of equivalent elastic strain. The scanning regions achieve high thermal stress due to them being restricted (not free to expand).

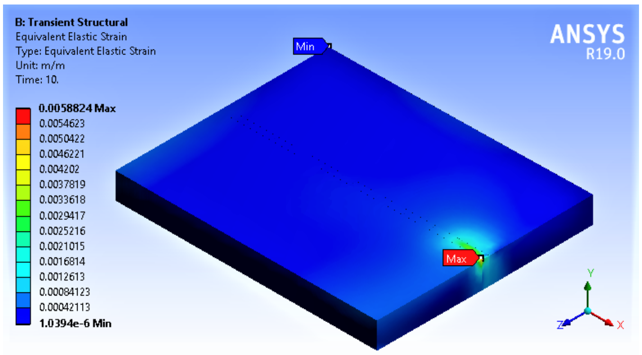

Fig. 12. Distribution contour of equivalent elastic strain at *t*=10 sec and laser power 150 W.

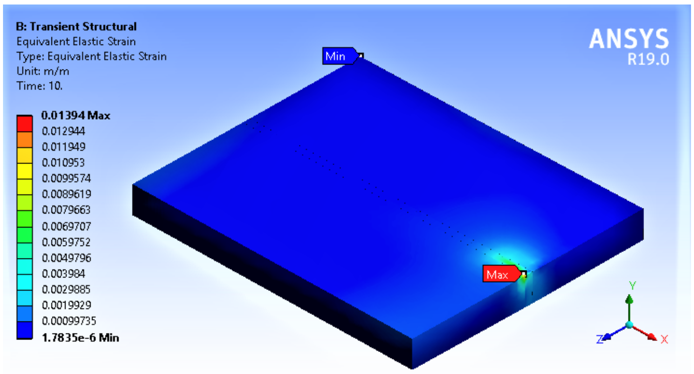

Fig. 13. Distribution contour of equivalent elastic strain at *t*=10 sec and laser power 200 W.

6. Comparison

Figure 14 illustrates an analytical comparison between current study model and Sharma's analytical model [6]. According to the figure above there is a good agreement in results for both models where the two studies used the same laser power "200 W'. Furthermore, the two models implement same laser cutting technique ND: YAG straight pulsed laser, the gap between the lines is due to many causes such as; the type of material. The material used in the current study is 2024-T3 aluminium alloy instead of Sharma's material "pure aluminium alloy 2024" and also the thermal and mechanical properties for both materials are different due to difference in Chemical compositions, as well as the type and size of the mesh have a significant role in the precision of the numerical results.

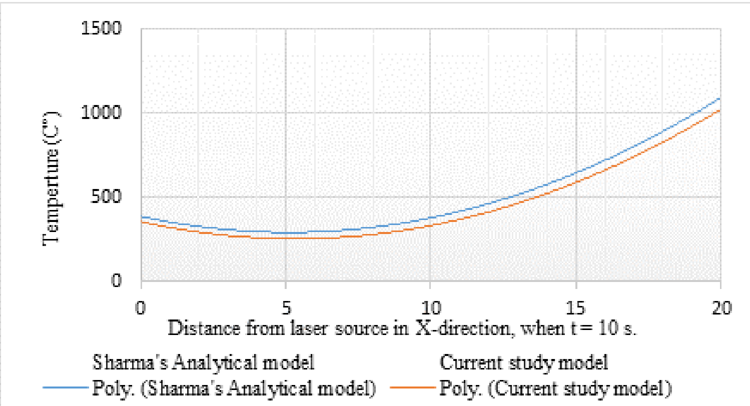

Fig. 14. Comparison of current study model and Sharma's analytical model for temperature distribution.

6. Conclusions

The use of a modelling method is in predicting cutting zone specifications that will provide safe take, less expensive and accurate results in testing the possibility of fabrication of aircraft structure pieces with optimal ends finishing, in terms of less distortion and cracks. Nd: YAG pulsed laser cutting technique was numerically investigated using the Finite Element Method. ANSYS Parametric Design Language (APDL) was adopted for studying and analysing the effect of laser power on thermal and mechanical stress of the cutting edge. Some concluding results are given below:-

- The maximum value of laser power located in the beam centre produce a temperature reaches to melting temperature of the material.
- The heat conduction affects positively on the cutting process due to preheating of the frontal region by the thermal power of the laser before proceeding with the cutting process.
- Due to the high reflectivity of aluminium alloy surface which resulted in difficulty in the cutting process. However, smooth operation could be achieved over increasing the laser power with constant scanning speed.
- The high thermal conductivity of aluminium increases the conduction process from a heated region to solid bulk. High thermal gradients can be observed at the surface of the workpiece because the thermal conductivity is highly affected by temperature.
- The temperature of the laser heated spot raises by 46% at elevated laser power reaching as high as 200 W.
- Von-Mises stress records high values approaching to 4.7 $*10^8$ Pa at the scanning line regions "cutting edge" of the material.
- The magnitude of thermal stress at the scanning line regions 'cut-edge' reaches to high values, due to these edges are not free to expand, as well as maximum values of elastic strain can be noticed at these regions.

Nomenclatures

$[C]$	Matrix of specific heat
$c(T)$	Specific heat as a function of temperature, J/kg. K
E	Young's modulus
$F(t)$	External load vector
$F_{th}(t)$	Vector of temperature load
h	Heat transfer coefficient, W/m^2 .K
I_0	Intensity of laser at (0,0), W/cm^2
$[K]$	Matrix of conductivity
$K(T)$	Matrix of temperature dependent stiffness
$k(T)$	Thermal conductivity as a function of temperature, W/m. K
$\{Q\}$	Vector of nodal heat flow
Q_{in}	Heat generation rate, W/m^2. K
R	Surface reflectivity
r	laser beam radius, mm
$\{T\}$	Nodal temperatures vector
$\{\dot{T}\}$	Vector of Time derivative of {T}
T_{ext}	External temperature (293.1), K
$\{u(t)\}$	Vector of displacement
x,y	Distance from centre (0,0) of the laser beam in x and y direction, m

Greek Symbols

α	Thermal expansion coefficient.
ν	Poisson's ratio
ρ	Density of material, kg/cm^3

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