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A Study of Temperature Distribution for Laser Assisted Machining of Ti-6Al-4V Alloy

Ajit Joshi[1], Neel Kansara[1], Subhankar Das[1]*, P. Kuppan[1], K. Venkatesan[1]

[1]School of Mechanical and Building Sciences,VIT University ,Vellore 632014, India
Email address: neel.kansara@gmail.com.

Abstract

Laser Assisted Machining (LAM) involves machining the workpiece after softening it with laser emitted heat. This paper includes the study of temperature distribution across depth of the workpiece. A finite element model of transient temperature distribution problem is developed. The variation of thermal properties of the Ti-6Al-4V titanium alloy is considered. The Gaussian beam profile of the laser spot is selected for analysis. The effect of various input parameters like spot radius, laser power and scanning speed is studied. The parametric studies showed that the temperature of the workpiece increases with laser power and decreases with increase in spot radius and scanning speed.

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*Keywords:*Laser Assisted Machining;Preheating-Temperature;Ti6AL4V

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1. Introduction

Titanium alloys are widely used in automotive industries and aerospace industries. These alloys usually have high strength to weight ratio and good corrosion resistance at high temperatures. Due to the presence of alloying elements, it is very hard to machine such alloys. Conventional machining of titanium alloys is a low productivity process as it results in high cutting forces which thereby decrease tool life which results in high tool cost.

Laser Assisted Machining (LAM) can be considered as an alternative for machining hard to machine titanium alloys. Laser beam machining is performed by heating the workpiece just ahead of the cutting tool with the help of a laser beam. A localized heating is achieved due to laser beam. The laser can also have a very large range of wavelengths hence it is very easy to generate different amount of energies. It reduces the cutting forces and hence the tool wear is reduced and it also brings down the manufacturing time and cost.

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* Corresponding author. Tel.: 9629787106
E-mail address: subhankardas12@yahoo.co.in

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In LAM, ultimately the knowledge of the temperature distribution at the surface and depth of the cut is essential in determining the cutting parameters. Suthar et al. (2008) [1] discussed the temperature distribution for different cases including the laser intensity, depth of cut, cutting speed etc. with Gaussian intensity distribution Attia et al.(2010) [2] studied the high speed finish turning of the super alloy Inconel 718 under dry conditions. Inconel 718 is difficult to machine due to their low thermal conductivity and diffusivity, which causes steep temperature gradient at the tool edge and shift the location of maximum temperature towards the tool tip. Yang et al. (2010) [3] developed a finite element method for the moving Gaussian heat source for the laser assisted machining and the obtained numerical results were very close to the experimental values. Lei (2011) [4] developed a thermal model and experimental investigation for the laser assisted machining of the silicon nitride ceramic material. Masood et al.(2011) [5] presented the effect of laser parameters on temperature, cutting forces, surface profile, hardness and chip morphology. Rahman et al. (2012) [6] investigated the effect of different laser powers on the machinability of the Ti-6Cr-5Mo-5V4AL beta titanium alloy during the laser assisted machining. They found that beyond the feed rate of 0.25mm/rev and the cutting speed of 100 m/min, there was an insignificant difference in the cutting forces between the laser assisted and the conventional machining. Soni et al. (2013) [7] developed a two dimensional finite element model to analyze the effect of pulsed laser parameters such as pulse width, pulse frequency, radius of laser beam and peak power during drilling. Navass et al.(2013) [8] determined the laser parameters and the configuration in which for which highest force reductions are possible and reported that LAM improves machinability of Inconel 718. Tagliaferri et al. (2013) [9] discussed how the individual LAM parameters influence working temperature, heat affected zone extension and laser track width. Hyeon et al. (2014) [10] investigated the cutting forces and the preheating-predictions of the temperature for Inconel 718 and AISI Steel 1045 and the numerical analysis was validated with the help of the experiments conducted From the above literature it is evident that the important parameters which affect the performance of laser assisted machining are laser power, scanning speed and spot radius. Modeling of a thermal model considering these parameters is important as it gives required temperature at the desired depth of cut for effective machining.

Nomenclature

K	Thermal conductivity
T	Temperature
To	Ambient temperature
A	Absorptivity of the material
P	Laser Power
x	Co-ordinate in x-axis
y	Co-ordinate in y-axis
z	Co-ordinate in z-axis
b	Spot radius
t	Time
v	Scanning speed

2. Methodology

For determining the proper temperature distribution in the work material temperature dependent thermo-physical properties were feed into the model (Table 1). The laser beam profile was modeled using Gaussian function for the purpose of analysis. Since the laser heating is a transient heat transfer problem it is solved by using time load steps. The simulation was done using a commercial FEA code, ANSYS.

2.1 Finite element modeling of work piece

The dimension of the work material was taken as 30 mm × 20 mm × 5 mm in the rectangular shape (Fig. 1.a). The geometry was discretized using an eight-node hexahedral thermal element (SOLID Brick 70). The total number of elements in the model is 24000 and the total number of nodes is 27511.

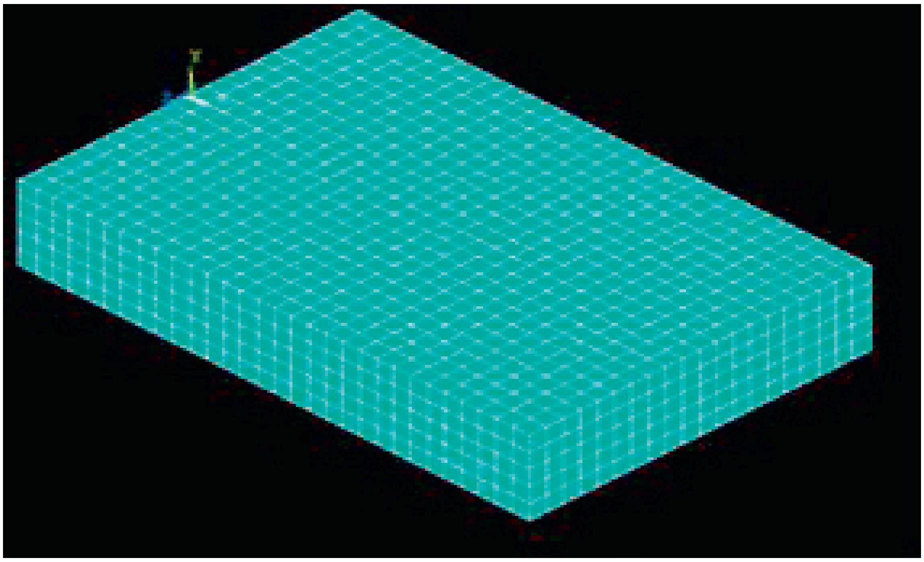

Fig. 1.a CAD model

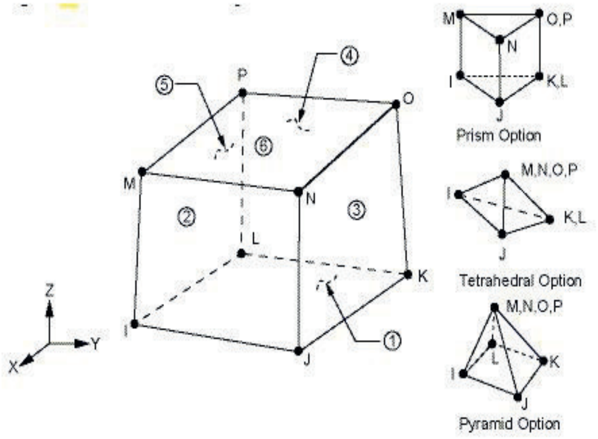

Fig. 1.b Element geometry Solid 8node 70

The geometry, node locations and the coordinate system for this element are shown in Fig. 1.b. The element is defined by 8 nodes and orthotropic material properties. A prism shaped element, a tetrahedral shaped element and a pyramid shaped element may also be formed. Orthotropic material directions correspond to element coordinate directions. The specific heat and density are ignored for steady state solutions. Convection, heat flux and radiation may be input as surface loads at element faces as shown by circled numbers in Fig. 1.b.

2.2 Material

The material used in this paper is Ti-6Al-4V. The thermo-physical properties such as thermal conductivity and specific heat are tabulated in Table 1.

Table1. Thermo-physical properties of the material [3].

Temperature (^{o}C)	Thermal Conductivity(W/m K)	Specific Heat (J/kg K)
25	7.0	546
100	7.45	562
200	8.75	584
300	10.15	606
400	11.35	629
500	12.6	651
600	14.2	673
700	15.5	694
800	17.8	714
900	20.2	734
	19.3	641
995	21	660
1100	22.9	678
1200	23.7	696
1300	24.6	714
1400	25.8	732
1500	27	750
1600	28.45	759

The absorbtivity of the material was calculated to be around 0.34 [3]. The heat transfer coefficient was taken to be 50 W/m^{2}K [3] and the initial temperature was taken as 22 ^{o}C [3] and the melting point of this titanium alloy was around 1660^{o} C [3]. The titanium alloy in particular is chosen because it is difficult to machine at temperature. It is being extensively used in the aerospace and medical applications.

2.3 Laser heat source modeling

The laser beam has different profiles as shown in Fig. 2 These profiles can be obtained depending on the lens employed and defocusing degree [10]. The Gaussian beam profile is the most preferred one among them because of its high power density and concentration of the heat over a very small area. The Gaussian laser beam is such that the intensity is highest at the center of the spot and the intensity reduces away from the center.

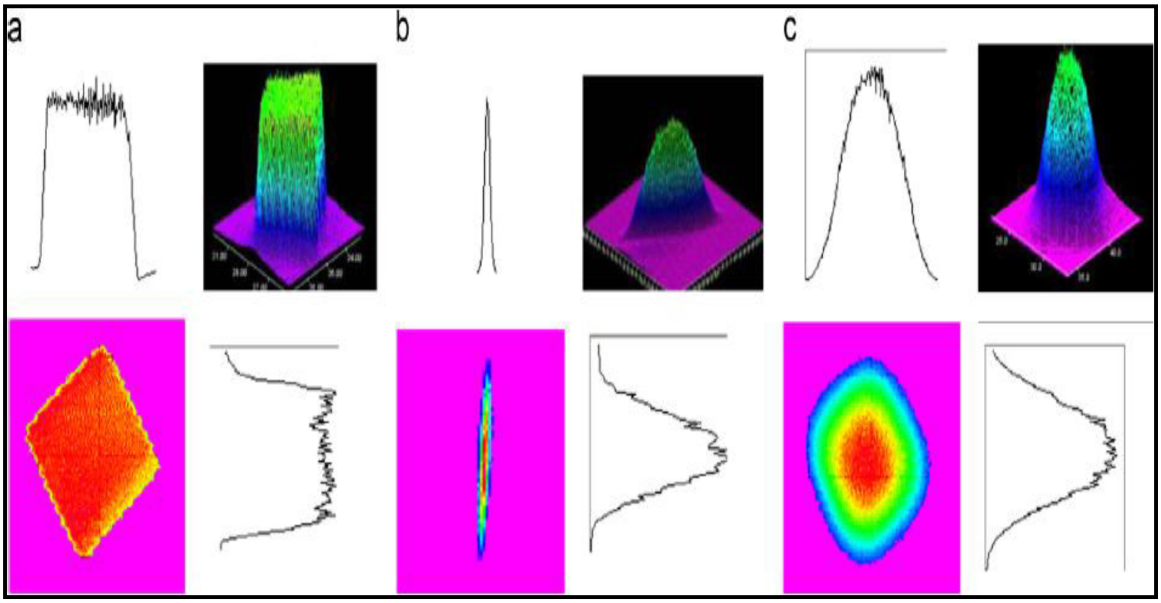

Fig 2 Laser spot profiles a.Square top hat energy profile, b. Elliptic Gaussian like energy profile, c. Nearly circular gaussian like enrgy profile [10]

The intensity of this Gaussian beam profile is given by the following equation [9].

$$I(x,y,z,t) = \frac{2P}{\pi b^2}\exp\left(\frac{-2(x-vt)^2+z^2}{b^2}\right) \tag{1}$$

The laser beam falls perpendicular on the surface of the workpiece and the ambient temperature was taken as 295 K.

2.4 Boundary And initial Conditions

The boundary conditions incorporated in this paper are convection applied on all the surfaces of the workpiece. The boundary condition and initial condition equation are given below.

$$-K\,\partial T/\partial z = q(x,y) - h(T - To) \tag{2}$$

$$T(x,y,z,t) = To \tag{3}$$

3. Results and Discussion

The laser parameters such as scanning speed, laser power and spot radius are varied during the FE simulation to study the effect of temperature distribution in Ti-6AL-4V work material. The results obtained from the simulation are presented in this section. Fig.3 shows the temperature distribution in the work material.

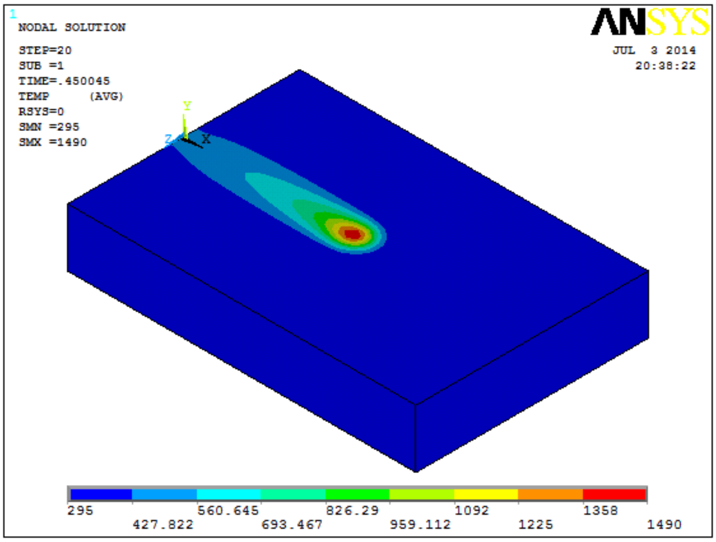

Fig.3 Temperature distribution during laser heating (laser power 500W, scanning speed 33.33mm/sec and spot diameter 1.5mm)

3.2 Parametric study

To understand the influence of laser parameters on temperature distribution and maximum depth up to which the desired temperature is obtained, a parametric study was performed by varying the laser parameters like scanning speed, spot radius and laser power. The Figs. 4 – 6 show the results obtained by different combinations of laser parameters.

Fig. 4 depicts the effect of laser power on temperature distribution along the depth. The temperature of the work piece increases with increase in the laser power. The reason for this can be justified by the fact that more the intensity of laser falling on the work piece higher the temperature, however too much temperature rise can result in melting of the work piece which is not desirable for laser heating applications such as laser assisted machining. Hence for the high laser power we can change the other two parameters to get the desired temperature. The trends of the results obtained from the present analysis agrees with results of Masood et al. [6].

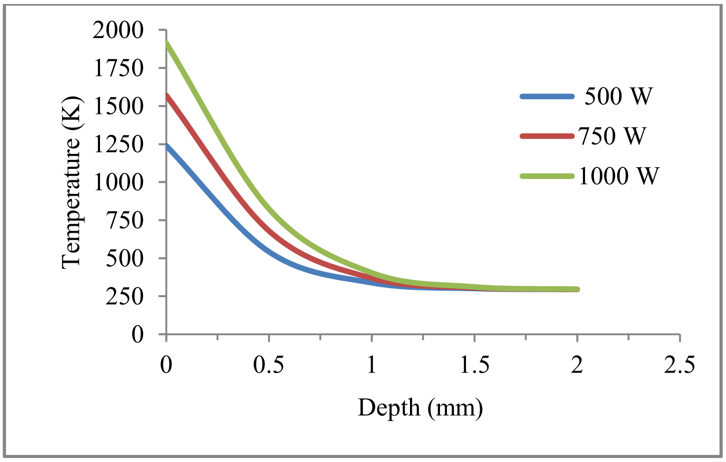

Fig. 4 Temperature Vs depth at different laser powers (at constant scanning speed of 66.66 mm/sec and spot radius of 1.5 mm)

The effect of laser spot size on temperature distribution at the depth of cut is shown in Fig. 5. It is very clear from the simulation results that the temperature increases with the decrease in laser spot size. It could be attributed to the fact that as the laser spot size is increased for a given power the laser irradiation is distributed over a much larger area which ultimate resulted in less temperature rise of work piece at surface and in depth of cut. The results obtained are in agreement with the work of Soni et al. [7].

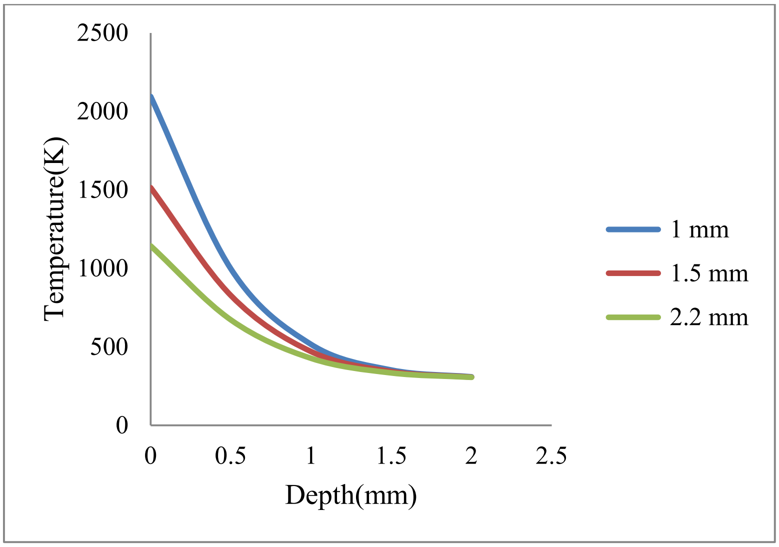

Fig. 5 Temperature Vs depth at different spot radii (at constant scanning speed of 33.33 mm/sec and lase power of 500W).

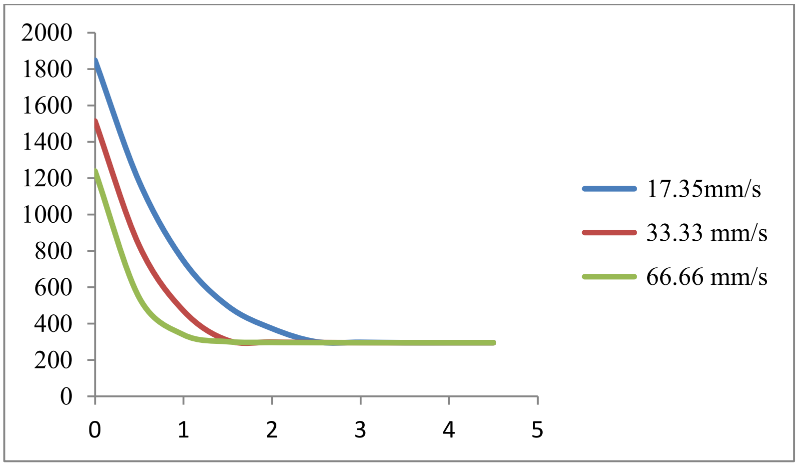

Fig. 6 Temperature Vs depth at different scanning speeds (at constant spot radius of 1.5 mm and power of 500W).

Fig. 6 shows the effect of laser scan speed on temperature distribution at the depth of cut. The temperature of the workpiece decreases with increase in scanning speed. This is justified by the fact that when the laser's spot progresses over a workpiece there is overlapping of the adjacent laser spots. Due to the overlapping there is addition of intensities of the adjacent laser spots on the workpiece. If the scanning speed is low there will be more overlapping of the adjacent laser spots which leads to higher temperature. If the scanning speed is high, less overlapping will take place thereby giving less temperature rise in the workpiece.

4. Conclusion

The finite element analysis was performed to study and predict temperature distribution in the workpiece and also to predict the depth at which the desired temperature is obtained to establish the optimum depth of cut for laser assisted machining. The laser parameters such as laser power, scanning speed and spot radius were selected and the combinations of these parameters were considered for the thermal analysis. The following conclusions were drawn based on the FE simulation:

- At laser power of 1000 W, 66.67 mm/s scanning speed and 1.0 mm spot size the temperature of the workpiece is going beyond the melting point of the titanium alloy which is not desirable for LAM.
- For laser power of 1000 W at 0.5mm depth, temperature reached 823 K with scanning speed 66.67 mm/s and spot radius 1.5 mm. For the same spot radius and scanning speed the temperature obtained at 0.5 mm depth for the laser power 500 W and 750 W are 541 K and 679.32 K respectively.
- For a spot radius of 1 mm, power of 500W and scanning speed of 33.33 mm/sec the maximum temperature reached is beyond the melting point of the alloy which is not desirable for LAM. On the other hand the spot radius 1.5 mm and 2.2 mm gave the temperature at 0.5 mm depth to be 827 K and 687.95 K respectively.
- At scanning speeds of 33.33 mm/s and 66.66 mm/s the temperature obtained at depth of 0.5 mm are 827 K and 541.95 K respectively for power 500 W and spot radius 1.5 mm.
- The FE simulation results would be highly helpful to select the optimum laser parameters for laser assisted machining.

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