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Finite Element Modelling of Laser Beam Machining For Titanium 5553 Alloy

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Abstract Aerospace industry has been thriving for the past few decades and with passage of each decade we have been trying to achieve faster and lighter spacecraft. One of the major fields of research is the material being used. Super alloys possessing high strength to weight ratio, corrosion resistance and higher thermal adherence have been under scrutiny. Titanium alloy 5553 (Ti-5Al-5V-5Mo-3Cr) is a near beta alloy with sublime hardenability and strength characteristics and is a promising substitute for present options. As the traditional methods are incompetent to machine the super alloys, a modern machining process such as laser beam machining has been suggested.

At present work, a symmetrical work piece in suitable dimensions is modelled using 3D modelling. This model is used for developing a finite element model of laser beam machining for selected material and steady state followed by the transient thermal analysis is carried on the same model in order to predict the temperature distribution and heat affected zone around the machined area using finite element analysis software.

Index Terms **— finite element model, titanium alloy, transient thermal analysis, heat affected zone.**

I. INTRODUCTION

Laser Beam Machining (LBM) is one of the unconventional methods of machining the materials of higher hardenability characteristics. Conventional machining tends to produce greater forces to act upon the substance which may not be suitable for the material and thus the LBM comes into play as it is indeed more associated with the material properties such as the thermal conductivity and specific heat as well as melting and boiling temperature. Increasing demand for advanced difficult-to-process materials and the availability of high-power lasers have stimulated interest in research and development related to laser machining.

As the laser falls on to the surface the un-reflected light is absorbed by the surface. When sufficient power is achieved the surface melts and vaporizes. The process is difficult and complex due to the scattering and reflection losses at the machined surface. Also the heat diffusion into the bulk material causes phase change, melting and vaporization. Depending upon the power density and the time of beam, the mechanism progresses from heat absorption to the melting and vaporization. High intensity of laser beam is not recommended as it may cause the formation of plasma and dwindle the efficiency of the process due to the scattering and absorption losses. The rate of machining depends upon many factors and parameters such as the laser power, pulse duration, spot diameter and many others. Machining by laser occurs when the power density of the beam is greater than what is lost by conduction, convection, and radiation, and moreover, the radiation must penetrate and be absorbed into the material.

The relatively lower mass for a given strength level and its resistance to the high temperature makes titanium an appropriate metal to be used in various fields majorly the aerospace industry. It has been used to construct the front engine parts and rotor blades as well as the landing gear components of the aeroplanes. Titanium alloy 5553 is a relatively new metal used in the aerospace sector due to its outstanding properties. It comes under the category of super alloys which have sublime hardenability and strength characteristics. Titanium 5553 (Ti-5Al-5V-5Mo-3Cr) is a near beta alloy which is readily heat-treatable, generally weld able, and has high strengths. Excellent formability can be expected in the solution treated condition. Beta alloys have a good combination of properties for sheet, heavy sections, fasteners, and spring applications.

II. LITERATURE

J. W. Jung et al [1], presents the deformation errors caused by thermal effects in the laser-assisted machine tool. Laser assisted machine tool performs the localized heating and cutting process simultaneously. So, the heats generated by localized heating process as well as the cutting process are conducted into cutting tool. In order to predict deformation errors, the heats from the two heat sources have to be analysed simultaneously and thermal distortion have to be calculated. The procedure for predicting the thermal distortion by laser power and cutting temperature had presented. Total procedure has presented in sequence of of three steps. First step, the commercial software Sim designer was used to analyse temperature distribution of material removal plane by moving heat source. Second step, after defining result of the analysis first step, commercial software AdvantEdge was used to calculate the cutting temperature by modelling a simple orthogonal cutting. Third step, the commercial software Simdesigner was used to analyse thermal distortion by inputting the calculated cutting temperature and force by the second step. The results can be used to increase the cutting accuracy by compensating thermal distortion prior to laser-assisted machining.

Chithirai Pon Selvan M et al [2], presents a review on the conclusions of the various research papers available on laser beam machining on the various properties that affect the quality of the process such as heat affected zone formed in the work-piece, laser cut quality and why laser beam machining is more advanced than the other machining processes.

Stewart and David et al [3], presents the microstructure and material properties of the workpiece titanium 5553. This article summarizes the experimental casting studies carried out including castability, microstructure/property correlation, and evaluation of a bulkhead casting, property assessments, and manufacturability.

In the present research work, a finite element model of a component is developed using plane 55 axisymmetric element in ANSYS. This model is used for further analysis i.e. transient thermal analysis in order to predict the temperature distribution and heat affected zone around the machined area.

III. TITANIUM 5553 ALLOY

The relatively lower mass for a given strength level and its resistance to the high temperature makes titanium an appropriate metal to be used in various fields majorly the aerospace industry. It has been used to construct the front engine parts and rotor blades as well as the landing gear components of the aeroplanes. Titanium alloy 5553 is a relatively new metal used in the aerospace sector due to its outstanding properties. It comes under the category of super alloys which have sublime hardenability and strength characteristics. Titanium 5553 (Ti-5Al-5V-5Mo-3Cr) is a near beta alloy which is readily heat-treatable, generally weld able, and has high strengths. Excellent formability can be expected in the solution treated condition. Beta alloys have a good combination of properties for sheet, heavy sections, fasteners, and spring applications

Table I
Properties of Ti 5553

PROPERTIES	**VALUE**
1. Thermal conductivity ($Wm^{-1}K^{-1}$)	5.8
2. Specific heat ($JKg^{-1}K^{-1}$)	550
3. Density (Kgm^{-3})	4670
4. Ultimate tensile strength (MPa)	1159
5. Yield strength (MPa)	1055
6. Elongation percentage (%)	9
7. Compressive strength (MPa)	1138
8. Shear strength (MPa)	690

Table II
Chemical composition of Ti 5553

Ti 5553	Ti	Al	V	Mo	Cr	Fe
Min	Base	4.4	4.0	4.0	2.5	0.3
Max	Base	5.7	5.5	5.5	3.5	0.5

IV.BOUNDARY CONDITIONS

In present analysis, the convection co-efficient of heat transfer, heat input and ambient temperature are applied as boundary conditions. The heat input based on different laser powers are calculated as follows and it will be used in analysis.

The rate of machining depends upon many factors and parameters such as the laser power, pulse duration, spot diameter and many others. Machining by laser occurs when the power density of the beam is greater than what is lost by conduction, convection, and radiation, and moreover, the radiation must penetrate and be absorbed into the material. The power density of the laser beam, P_d is given by

$P_d = 2L_P / (\pi F_1^2 \alpha^2 \Delta t)$

Where size of the spot diameter

$d_s = F_1 \alpha$

P_d = power density, W/cm^2

L_p = laser power, W

F_1 = focal length of lens, cm

T = pulse duration of laser, s

In present analysis, the convection co-efficient of heat transfer, heat input and ambient temperature are applied as boundary conditions. The heat input based on different laser powers are calculated.

Table III
Heat calculation for different boundary conditions values

Power (W)	Pulse time (ms)	Heat(W)(*10^7)
200	0.2	39.78
	0.4	19.89
	0.6	13.263
250	0.2	49.735
	0.4	24.86
	0.6	16.57
300	0.2	59.683
	0.4	29.84
	0.6	19.894

V.RESULTS AND DISCUSSION

Temperature distribution occurs in axial way in all direction and this temperature distributes along the node by node in a decreasing manner. The first phase of the results include the temperature variation of the substance when the laser acts upon it and the second includes the death element analysis results. The below given Finite Element Models obtained show the heat affected zone for the material when various heat input is applied when changes in pulse time and power occur. These results are plotted on the graph against values of temperature and other variables.

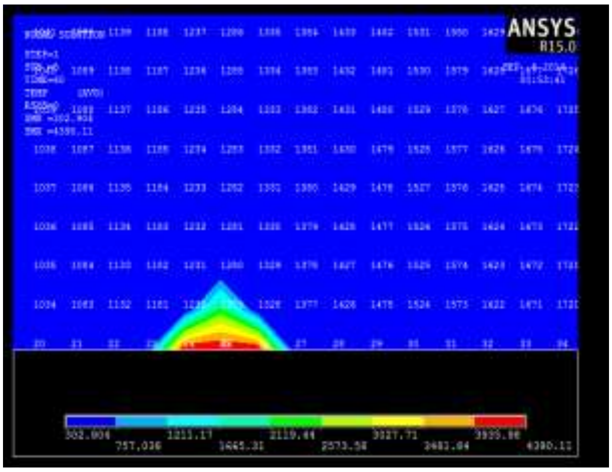

Fig .1 When power of 200 W and a pulse time of 0.2 millisecond is applied

From fig 1, it is inferred that when a power of 200 W is applied on to the titanium alloy surface with a pulse time of about 0.2 millisecond, a maximum temperature of about 4390.11 is reached and the nodal temperature can be easily differentiated within the ANSYS results which are further presented in the graphical format.

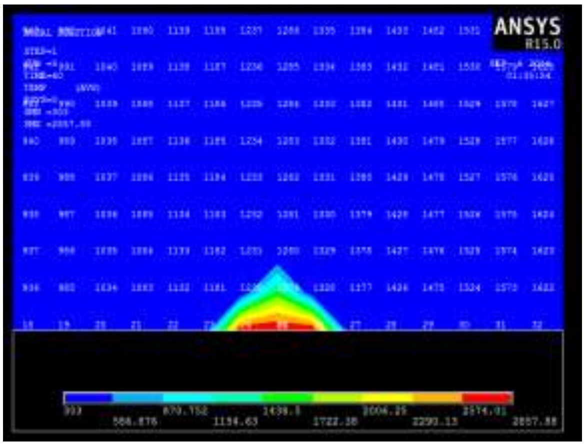

Fig .2 When power of 250 W and a pulse time of 0.4 millisecond is applied

From fig 2, it is inferred that when a power of 250 W is applied on to the surface for a pulse time of 0.4 millisecond a maximum temperature of about 2857.88 K is achieved which further stems down to 870.52 K when reaching the third node.

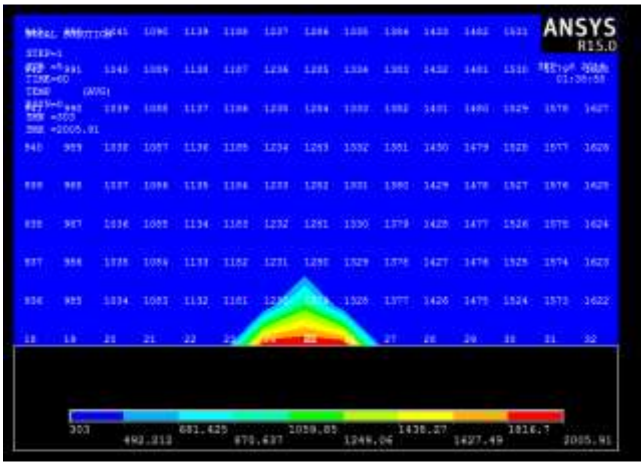

Fig .3 When power of 250 W and a pulse time of 0.6 millisecond is applied

From fig 3, it is inferred that when a power of 250 W is applied on to the surface for a pulse time of 0.6 millisecond a maximum temperature of 2005 K is achieved which dwindles to 681 K within 2 nodes. These ANSYS results show the heat affected zone very clearly and this can be further shown in graphical format.

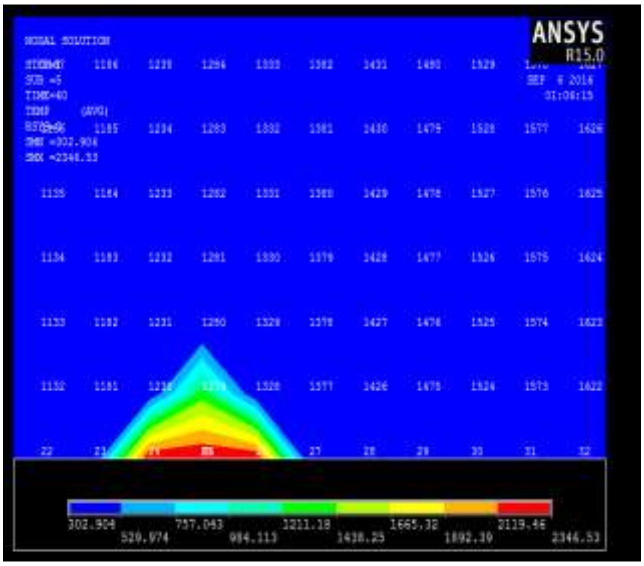

Fig .4 When power of 300 W and a pulse time of 0.6 millisecond is applied

From fig 4, it is inferred that when a power of 300 W is applied on to the surface for a pulse time of 0.6 millisecond a maximum temperature of 2346 K is achieved which dwindles to 757 K within 2 nodes. These ANSYS results show the heat affected zone very clearly and this can be further shown in graphical format as shown below.

Table IV

Temperature at different nodes with variation in centre distance (for pulse duration 0.4 ms)

centre distance (mm)	Temperature (K) (p=250W)	Temperature (K) (P=200W)	Temperature (K) (P=300W)
0	2857.88	2346.53	3369.68
1	2574.01	2119.46	3028.94
2	586.876	529.974	643.74

The detailed graphical representation for every case is plotted below. The temperature variation for subsequent centre distance is noted down for different power of laser for a pulse duration of 0.4 millisecond. The maximum temperature varies from 2857.88 K to 586.876 K as we move from centre distance to the other nodes.

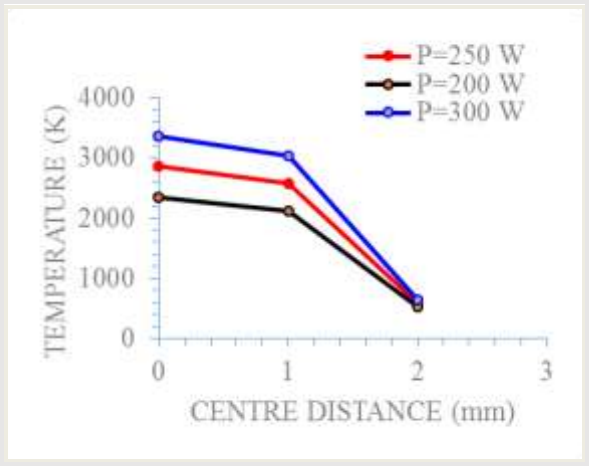

Fig .5 Temperature vs centre distance (pulse duration =0.4ms)

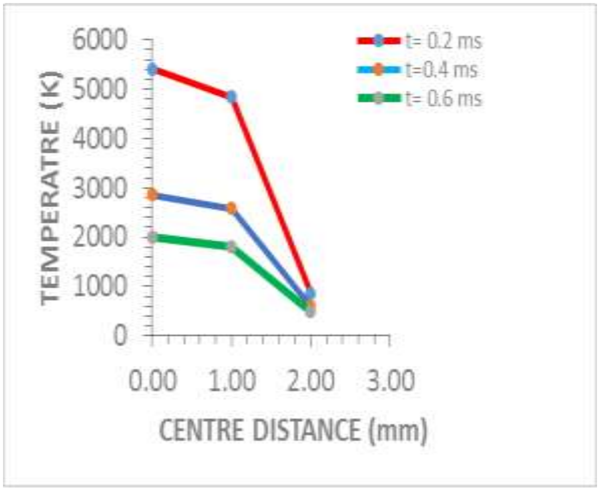

Fig .6 Temperature values at different nodes under pulse duration variation at P=250 W

From fig 6, it can be inferred that the temperature variation of a laser of power 250 W is shown with variation in centre distance for different pulse duration time, the maximum temperature at the centre of the laser beam decreases from 5414 to 870 as shown in the graph which gives us an idea that a laser of pulse duration of 0.4 millisecond is the most suitable choice as it readily melts the material above 1965 K.

Table V

Temperature values at different nodes under pulse duration variation when P=250W

Centre Distance	Temp (K) (t=0.2) ms	Temp (K) (t=0.4) ms	Temp (K) (t=0.6) ms
0	6436.67	3369.68	2346.56
1	5755.15	3028.94	1892.39
2	984.519	643.74	529.97

From fig 7, it can be inferred that the temperature variation of a laser of power 200 W is shown with variation in centre distance for different pulse duration time, the maximum temperature at the centre of the laser beam decreases from 4390.11 to 757.038 as shown in the graph which gives us an idea that a laser of pulse duration of 0.2 millisecond is the most suitable choice as it readily melts the material above 1965 K.

Table VI

Temperature values at different nodes under pulse duration variation when P=200W

Centre Distance	Temp (K) (t=0.2) ms	Temp (K) (t=0.4) ms	Temp (K) (t=0.6) ms
0	4390.11	2346.53	1671.51
1	3935.98	2119.46	1519.44
2	757.038	529.974	454.97

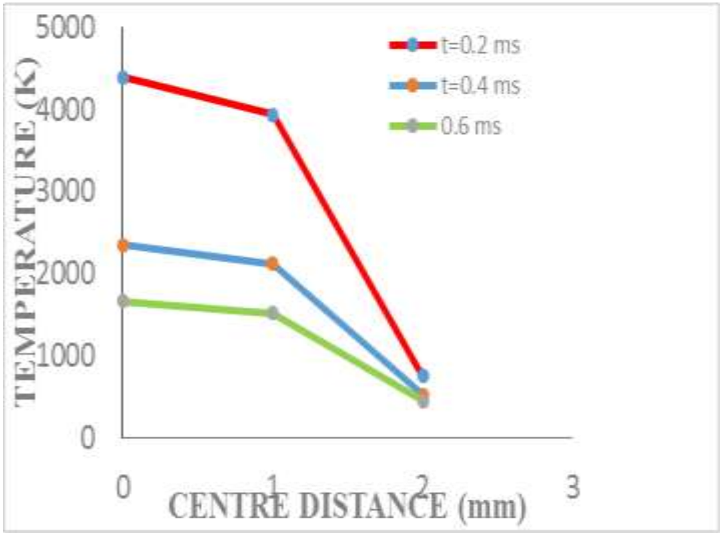

Fig 7 Temperature values at different nodes under pulse duration variation at P=200 W

From fig 8, it can be inferred that the temperature variation of a laser of power 300 W is shown with variation in centre distance for different pulse duration time, the maximum temperature at the centre of the laser beam decreases from 6436.67 to 984.519 as shown in the graph which gives us an idea that a laser of pulse duration of 0.4 millisecond is the most suitable choice as it readily melts the material above 1965 K.

Table VII

Temperature values at different nodes under pulse duration variation when P=300 W

Centre Distance	Temp (K) (t=0.2) ms	Temp (K) (t=0.4) ms	Temp (K) (t=0.6) ms
0	6436.67	3369.68	2346.56
1	5755.15	3028.94	1892.39
2	984.519	643.74	529.97

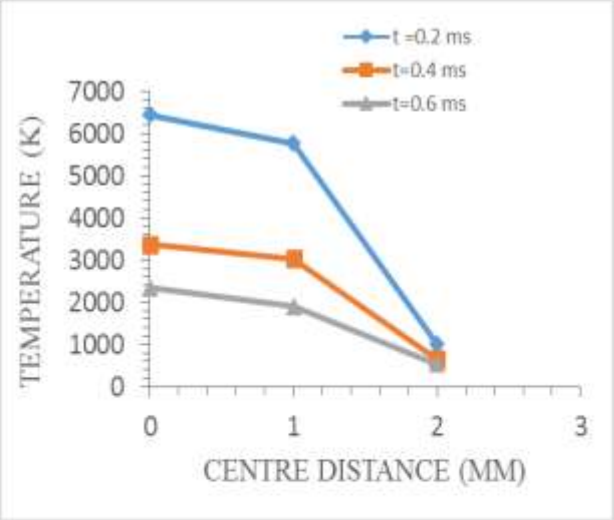

Fig 8 Temperature values at different nodes under pulse duration variation at P=300 W

VI CONCLUSION

The analysis of the given alloy of titanium machinable with a CO_2 laser of power varying between 150-300W as per suitable parameters is accomplished with the help of finite element analysis. The heat affected zone for the given material is calculated for different laser intensity values. The boundary conditions taken were ascertained to be correct upon getting desirable results from software analysis.

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