

Numerical Simulation and Microstructural Exploration in Laser Welding of Ti-6Al-4V

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Abstract

In this study, a numerical simulation of laser welding process is described in detail. A 3-D finite element modeling is employed for this purpose using FEM package of ANSYS® 14.5.3-D Gaussian heat distribution of conical heat source moving with constant traverse speed is considered for performing thermal analysis. The variation in material properties of Ti-6Al-4V with respect to temperature is considered during simulation. The convective and radiative modes of heat transfer are also incorporated in boundary conditions. The influence of welding power on temperature contour and aspect ratio of weld bead are explored. It is observed that the bead width and penetration depth is strongly affected by the imposed beam power. The microstructural study is also conducted inside the weld bead for fully penetrated weldment. The fully martensitic structure is developed in the fusion zone. The beauty of the present model is that it will help to optimize the laser welding parameters and also it will be helpful to estimate the temperature field at different location of the weldments.

Keywords: Laser welding, Ti-6Al-4V alloy, Gaussian heat source, Microstructure, Martensite

1. Introduction

A lightweight structure is successfully made by the virtue of the selected optimized combination of material, their specific design and well defined manufacturing process. Whenever the lightweight structure made by titanium and their alloys are required welding is the most appropriate joining technology available yet. The first ruby laser was made in 1960 and its application in manufacturing industries was started in 1962. However, for the welding purpose the use of laser beam welding (LBW) was reported in 1971. Since, then the application of LBW in the industrial application was grown massively [1-3]. Laser beam have a high degree of spatial coherence, which leads to a high beam quality. Laser beams exhibit good focus-ability with very

low beam divergence with intended path. Now a day, its demand in manufacturing industries is increasing due to its lower production cost, rapid production capability, minimum distortion and high efficiency compared to other successful joining technologies[2-6].

LBW is a non-conventional, non-contact and advanced technique for welding of similar and dissimilar materials. There are a lot of disadvantages which is associated with traditional arc welding process such as necessity of groove preparation, low welding speed, high heat input, difficult to weld intricate shape, larger size of fusion and heat affected zone and it yields high distortion in the weldments. To overcome these issues laser beam is widely adopted for welding purpose in many industries such as automotive industries, microelectronics, aerospace, nuclear, marine and petrochemical industries[7-10]. Among all of the entire available laser heat source, fiber laser gained great popularity due its high beam quality, compact design, light weight, high speed, and good flexibility. Fiber laser beam can be used for joining different grades of titanium alloys. The controllable factors in LBW process are beam spot radius, beam power and traverse speed [11-13].

The properties of titanium and their alloys make a bridge between the idyllic characteristics of aluminium and different categories of steel. Ti-6Al-4V alloy has supreme combination of strength and ductility. Hence, its utilization in several industries i.e. automobile, aeronautics, and petro-chemical industries etc. It possesses excellent combination of light weight and moderate corrosion resistance [14-15]. Laser beam welding is a complicated process including large number of input parameters. But, this process is stochastic in nature. Due to this, to obtain the optimum parameters just by trial-and-error technique is very challenging task. In order to reduce experimental cost in trial and error experiments and to improve the joint quality, numerical simulation based on finite element method (FEM) can be the powerful tool. The schematic diagram of workpiece dimension and LBW experimental setup are depicted in Figs. 1 and 2, respectively.

Now-a-days the demand for numerical simulation is progressively increasing to achieve optimum process parameter in order to reduce experimental costs. The thermo-mechanical analysis in welding is studied by many investigators by analytical as well as numerical approach. Goldak et al. [16] consider the non-symmetric double-ellipsoidal shape of moving heat source during simulation of welding experiments without considering the temperature dependent material properties of the weldments.

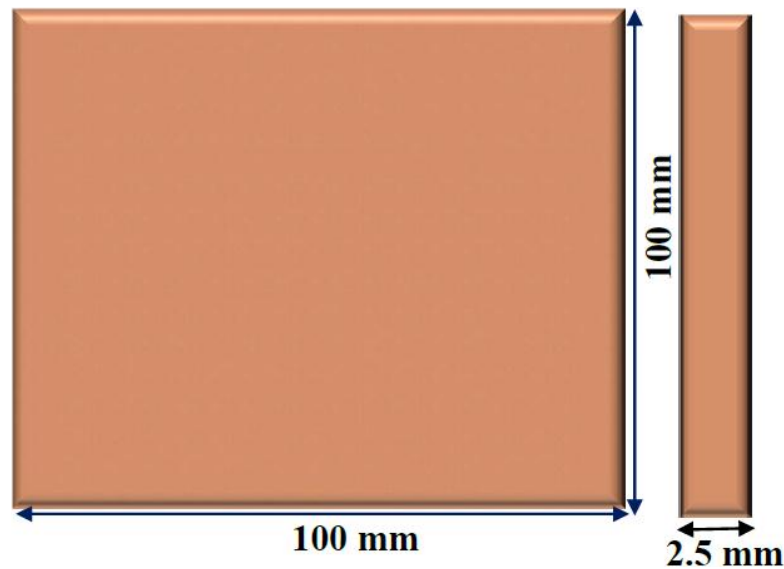


Fig. 1 Schematic diagram of workpiece and their dimension

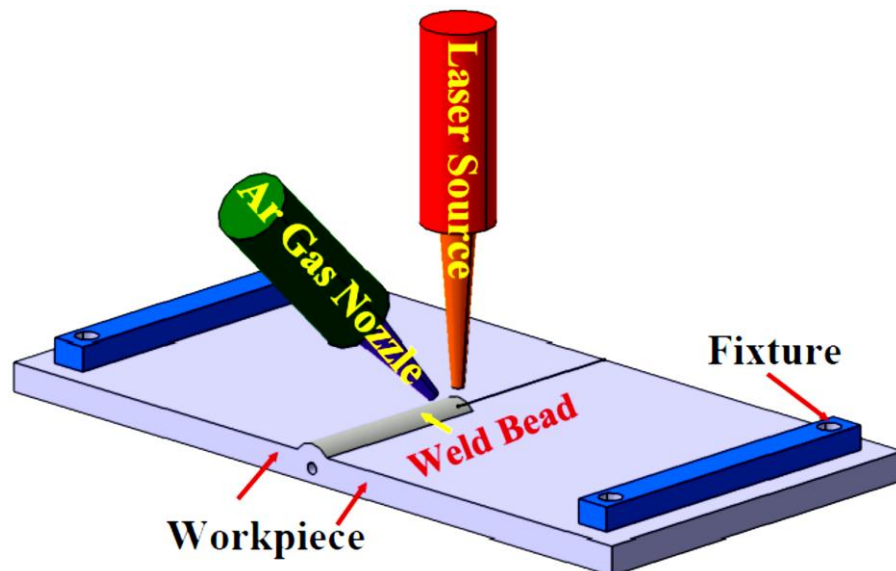


Fig. 2 Schematic of laser welding setup

A temperature profile was generated by Frewin and Scott [17] in Gaussian energy distribution of laser beam welding by using FEM. The obtained temperature histories in fusion zone and in heat affected zone from numerical simulation were approximately matched with the experimental results. To overcome the limitations of double ellipsoidal heat source model, Yadaiah and Bag [18] formulated a heat source having 'egg' configuration in ANSYS to simulate welding phenomena in both arc welding and LBW process. Akbari et al. [19] assumed 0.3 average absorptivity of Ti-6Al-4V material during finite element modelling of LBW process. The thermo physical property of Ti-6-Al-4V material was also included during the simulation. In this study,

the numerical simulation is carried out to find out the temperature profile in fibre LBW process. Also, the microstructure development in fusion zone is explored.

2. Workpiece Material

The Ti-6Al-4V alloy of industrial specification having grade-5 is selected for the simulation purpose in ANSYS[®] 14.5. The melting temperature of this selected alloy is in the range of 1653⁰C-1695⁰C depending on the presence of chemical constituents. In this study, 1700⁰C melting point of Ti-6Al-4V alloy is assumed for the generation of transient temperature profile. The elemental constituents are also presented in tabular form as shown in Table 1. The various kinds of thermo physical material properties like material conductivity (K₁), density (ρ), specific heat (C) and emissivity (ε) of Ti-6Al-4V are considered both the homogeneous as well as isotropic in nature [20].

Table 1 Elemental constituents of Ti-6Al-4V

Element	C	Al	V	Fe	H	N	O
Wt. %	< 0.08	< 5.5-6.75	3.5-4.5	<0.30	<0.015	<0.03	<0.25

3. Fundamental Equation

A three dimensional heat transfer equation for welding purpose can be written as

$$\rho C \left[\frac{\partial T}{\partial t} + (-V) \frac{\partial T}{\partial y} \right] = \frac{\partial}{\partial x} \left(K_1 \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_1 \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_1 \frac{\partial T}{\partial z} \right) + Q(x, y, z) \quad (1)$$

In Eq. (1),

Q(x, y, z) = Volumetric heat source and it depends on the welding power and speed

K₁ = Thermal conductivity of workpiece material

C = Specific heat

ρ = Density of workpiece

V = Traverse speed of heat source

4. Boundary Conditions

Initially during starting of the numerical simulation, the temperature of the workpiece is considered at room temperature as represented by Eq. (2).

$$T(x, y, z, 0) = T_o(x, y, z) \quad (2)$$

The boundary from which the heat is dissipated is shown in Eq. (3).

$$K_1(\partial T / \partial n) - q_0 + h(T - T_o) + \sigma \varepsilon (T^4 - T_o^4) = 0 \quad (3)$$

In Eq. 3,

K_1 = Thermal conductivity

q_0 = Heat flux (W/m^2 k)

σ = Stefan-Boltzmann constant

ε = Emissivity

T_o = Room temperature

To save the simulation time and accuracy of the model a lumped heat transfer coefficient (h_{lump}) is considered as per Eq. (4) developed by Frewin and Scott [17]. This Eq. 4 combinedly represent both radiative and convective heat transfer occurrences.

$$h_{lumped} = 2.4 \times 10^{-3} \varepsilon T^{1.61} \quad (4)$$

5. Heat Source, Simulation Procedure and Experimentations

In this section the shape of 3-D conical heat source is discussed which is used for transient analysis during numerical simulation of selected process and materials in finite element method (FEM). The selected heat source model made of two different portions as depicted in schematic diagram in Fig. 3. First part is considered as plane Gaussian heat source and second part is considered as conical shape. The plane Gaussian distribution heat distributed over top surface of the materials and conical shape is distributed along the thickness direction. During simulation, it is considered that 30% of beam power is absorbed by the top portion of workpiece material and

remaining 70% is absorbed by keyhole wall. The distribution of conical heat flux is expressed by Eq. (5).

$$Q(R, Z) = Q_0 \exp\left(-\frac{3R_e^2}{R_0^2}\right) \quad (5)$$

In the Eq. 5,

Q_0 = Maximum heat flux of heat source

R_0 = Heat distribution parameter,

R_e = Interior location coordinate

The TEM₀₀ transverse electromagnetic mode of laser beam is assumed throughout the analysis [21]. The Eq. 5 can also be expressed in X-Y coordinates as follows,

$$q_0(x, y) = \frac{3Q_{surf}}{\pi R^2} \exp(-3(x^2 + y^2)) \quad (6)$$

In Eq. 6,

Q_{surf} = Surface heat source and it is considered 30%

R = Heat source radius

R is calculated by using Eq. (7)

$$R = \frac{2M_0^2 \lambda f}{\pi D_0} \quad (7)$$

In Eq. 7,

M_0^2 = Beam quality and its value is 1 in case of ideal Gaussian beam

λ = Laser beam wavelength

f = Focal length of focusing lens

D_0 = Beam diameter (0.4 mm)

During simulation, it is assumed that the shape of the keyhole is conical. Therefore, Gaussian distribution of heat flux can be expressed as,

$$q(z) = \frac{Q_{keyhole}}{\pi R_e^2 H} \quad (8)$$

R_e = Average keyhole radius

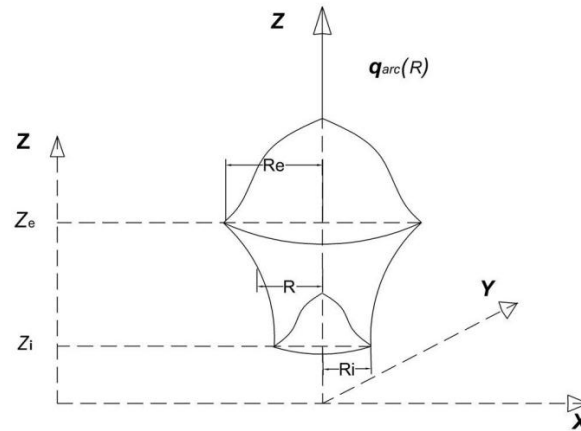


Fig. 3 Schematic diagram of Gaussian distributed laser heat source [21]

The numerical simulation is conducted in FEM package ANSYS® 14.5. During the simulation “SOLID70” element having eight-node is selected from the list of types of element module. The refined mesh along the welding direction (Fig. 4(a)) and non-uniform coarser mesh is generated in the remaining area. Based on the convergency test the six elements are selected towards the thickness direction. The six elements, yields reasonable convergency and taking acceptable solution time with excellent accuracy (Fig. 4 (b)).

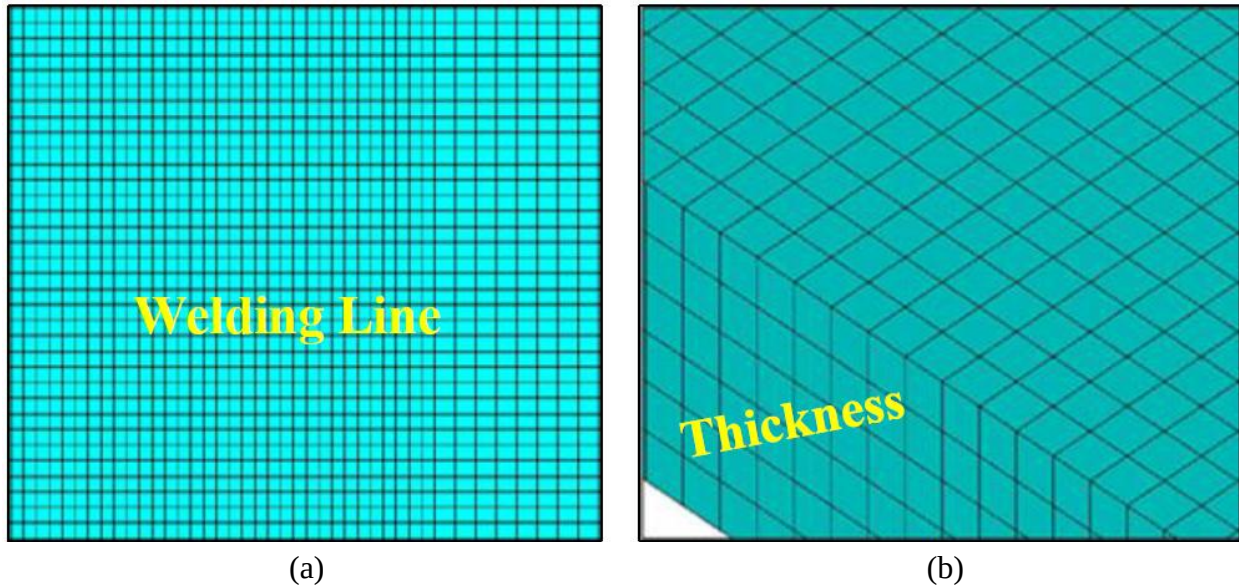


Fig. 4 Meshed workpiece along (a) weld line (b) thickness direction

The temperature dependent material properties are also incorporated in numerical simulation by providing the material properties at different temperature during the initiation of the simulation. For the parametric study, simulation is performed as per the selected parameters in Table 2 along with the actual welding experiment. The bead shape is defined from the melted and vaporized isotherm together. During experiment, the argon (Ar) gas is supplied on the top side of workpiece with flow rate of 5 lit/min as depicted in Fig. 2 to overcome the oxidation issue of the bead surface.

Table 2 Welding conditions

Power (Watt)	Welding speed (mm/min)	Beam angle (Degree)	Spot diameter (mm)
1100	450	90	0.4
1300			

6. Results and Discussion

The numerical simulation is conducted in ANSYS® 14.5 in two steps. Initially, the heat flux along with heat generation are given on workpiece surface. At the end of the first step, both the heat flux and heat generation is removed. Therefore, the heat transfer takes place from all the workpiece boundaries by means of both the well-defined convection and radiation modes of heat transfer.

6.1 Significance of beam power

Figures 5(a) and (b) show the effect of beam power on penetration depth and their shape. It is perceived that the aspect ratio of the weld bead is changed with increased beam power from 1100 W to 1300 W for a fixed traverse speed of 500 mm/min. The penetration depth is increased from 1.4 mm at 1100 W power to approximately full penetration at 1300 W power in the base plate of selected material. Similarly, the bead width is increased from 0.65 to at 1100 W to 1.4 mm at 1300 W. It is primarily due to the impact of increased value of line energy with increased beam power. The line energy (LE) is expressed by Eq. 9

$$\text{Line energy (LE)} = \frac{\text{Beam power (P)}}{\text{Welding speed (V)}} \quad (9)$$

From Eq. 9, it is found that with increase of beam power for a fixed traverse speed of 500 mm/min, the LE is increased. Therefore, higher beam power leads to more line energy at constant welding speed. Therefore, large amount of BM melts down and consequently penetration depth and bead width (Fig. 5) is increased.

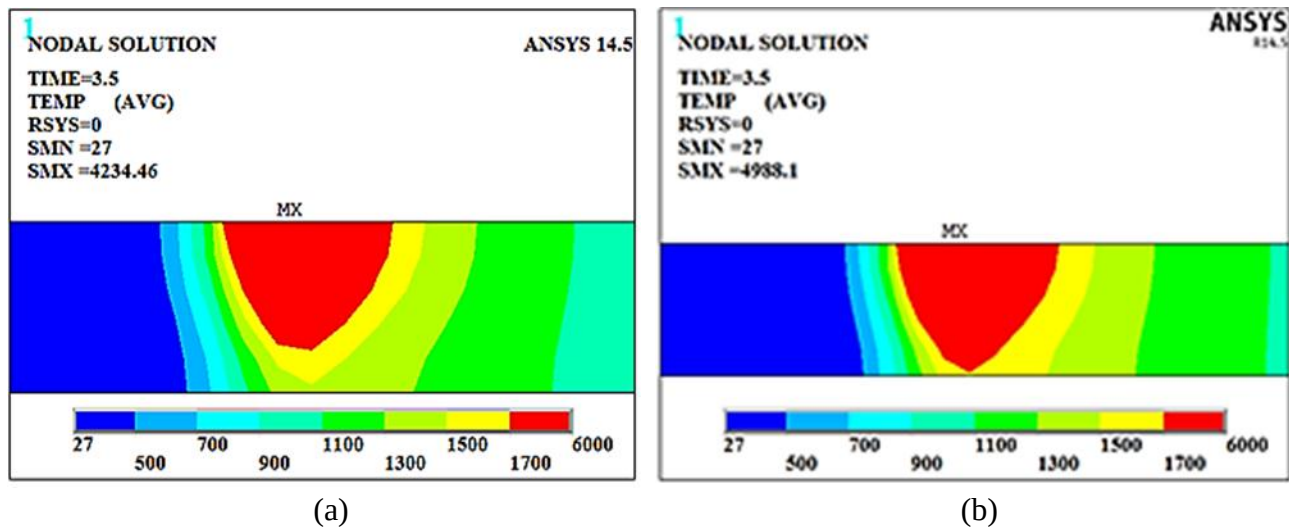


Fig. 5 Bead geometries at power of (a) 1100 W and (b) 1300 W at traverse speed of 500 mm/min

6.2 Distribution of Peak Temperature

Figure 6 depicts the influence of beam power on temperature distribution at a particular node along the welding line at a beam power of 1100 W and 1300 W for fixed traverse speed of 500 mm/min. From temperature profile it is clearly noticed that the peak temperature is increased as the beam power increases. It is prominently due to the increased value of power density over the workpiece with increased value of beam power at a fixed spot diameter of 0.4 mm.

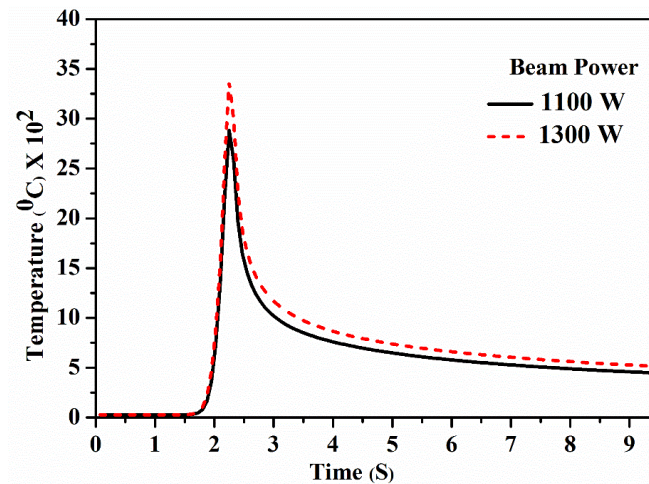


Fig. 6 Thermal history at specific node (a) 1100 W and (b) 1300 W for 500 mm/min speed
The relationship between beam power and power density is expressed by the relation as shown in Eq. 9. The relationship between the maximum temperature and the beam power is non-linear. The non-linearity occurs mainly due to the change in absorption coefficient of the workpiece material with the variation of temperature. Basically, the absorptivity is the surface characteristics and it also depends on the workpiece temperature. Probably the absorptivity does not varies linearly with respect to the surface temperature. Therefore, the non-linearity occurs between the peak temperatures with increased beam power. Inside the melted region the peak temperature reached above the melting temperature of Ti-6Al-4V alloy. It shows the clear evidence of melting inside this zone.

6.3 Microstructural Discussion

The microstructure inside the fusion zone of approximately fully penetrated weldment is explored with the help of field emission scanning electron microscopy image as depicted in Fig. 7. Fully α' martensitic micro-structure with needle shaped morphology is observed inside the FZ. The main cause of formation of α' martensite inside FZ is the rapid cooling of fused area. The rapid cooling is the features of LBW process. The minimum cooling rate of 410^0C is required to form α' martensite as discussed by the Ahmed et al. [22]. The observed microstructure clearly reflects that the cooling rate inside FZ reached above the minimum temperature required to convert the $\alpha+\beta$ phase to α martensitic phase.

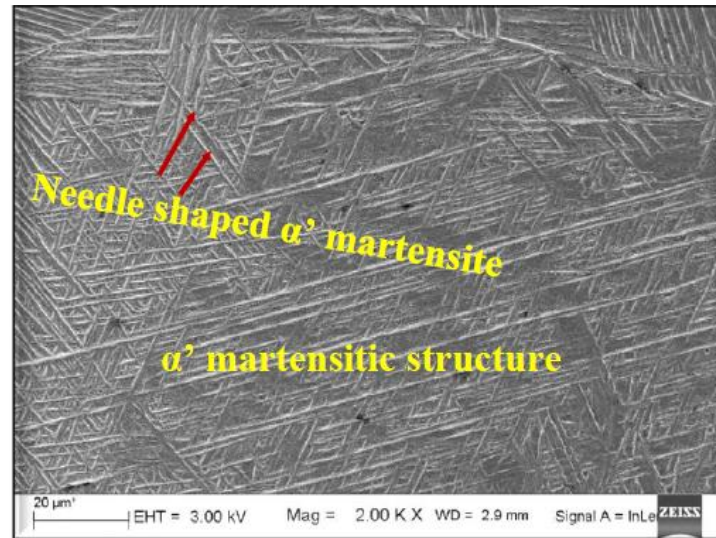


Fig. 7 Microstructure in fusion zone at beam power of 1300 W (FESEM image)

7. Conclusions

The conclusions from this current study are as follows.

- The penetration depth is increased with increasing value of beam power.
- The peak temperature inside FZ increases with increased value of power at a fixed traverse speed.
- The relationship between the peak temperature w.r.t beam powers is non-linear due to the variation of absorptivity coefficient of workpiece material of Ti-6Al-4V with rise in surface temperature.
- The martensitic structure is found inside the fusion zone with needle shaped morphology.
- The proposed model can be further used to explore the parametric effect on bead geometry for wide range of process parameters.

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