Evaluation of melt pool geometry during pulsed laser welding of Ti6Al4V alloy

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Abstract—In this paper, laser welding of titanium alloy (Ti6Al4V) is investigated as regarded a numerical and experimental study. Modeling for the temperature distribution is performed through a transient three-dimensional problem to predict the heat affected zone (HAZ), depth and width of the molten pool. The experiments were performed at different welding conditions to estimate the thermal model results with the depth, width and microstructure of the welded samples. It was observed that the thermal model was in good agreement with the experimental data. The model prediction error was found to be in the 2–17% range with most numerical values falling within 7% of the experimental values.

Keywords—Laser welding, Titanium alloy, numerical study, Temperature distribution.

I. INTRODUCTION

The increased interest by industry in laser welding is because this technique has shown high efficiency and low production cost compared to other welding methods. Laser welding can provide a significant benefit for the welding because of its precision and rapid processing capability. Titanium and its alloys have been widely used due to low density, good corrosion resistance, high operating temperature, etc. Some applications of titanium alloys in aerospace, biomedical, nuclear and automotive industries are reported by Wang et al. [1]. During the laser welding of Ti6Al4V alloy some sequential types of the phase transitions such as alpha–beta titanium trans-formation in the solid phase, melting, evaporation, ionization occur and then in the reverse order during cooling stage. Joining Ti6Al4V titanium alloys using pulsed Nd:YAG laser welding method was done by Akman et al. [2]. Their results showed that it was possible to control the penetration depth and geometry of the laser weld bead by precisely controlling the laser output parameters. Yang et al. [3] provided a finite element model to predict the depth and width of HAZ in laser heating of Ti6Al4V alloy plate and found that the depth and width of HAZ were decreased with an increase of laser scan speed. Frewin and Scott [4] produced a time-dependent 3D model of heat flow during pulsed Nd:YAG laser welding. By ignoring the convective flows in the melt pool and assuming a Gaussian energy distribution, they calculated transient temperature cross-sections along with the dimensions of the fusion and HAZ. They found that the fusion and HAZ produced numerically were extremely close to those produced experimentally. Review of aforementioned articles showed that various parameters were investigated in different studies. From each work, different aspects of laser welding were studied and therefore, different results were obtained, each of which could be useful in its position. However, no comprehensive study in these research fields was found to predict the width and depth of molten pool by using temperature history. We have carried out a numerical and experimental study of laser welding for modeling of temperature distribution and molten pool shape to predict the depth and width of the molten pool and HAZ dimensions. The objective of this paper was to examine the effect of welding speed on the temperature distribution, weld depth and weld width.

II. EXPERIMENTAL SETUP

Experiments were performed to characterize the temperature measurements and HAZ dimensions in laser welding. The sample was Ti6Al4V alloy plate (50 mm × 20 mm with the thickness of 3 mm). A model IQL-10 pulsed Nd:YAG laser with a maximum mean laser power of 350 W and wavelength 1.06 μm was used as the laser source. The laser parameter ranges were 0.2–25 ms for pulse duration, 1–1000 Hz for pulse frequency and 0–40 J for pulse energy. The spot diameter on the surface of the plate was set at about 0.7 mm. For the purpose of shielding, the pure argon gas from a coaxial nozzle was used with the flow rate at 15 l/min. Fig. 1 shows a schematic illustration of the experimental setup. K-type thermocouples with an operative range between -40° C and +1260° C and the accuracy between ±1% were used for temperature measurement. Because the temperature of the molten pool was very high, the thermocouples were attached
on the top surface at 2 mm lateral distance from the center of the molten pool. The locations of thermocouples are specified in Fig. 1 (points A and B). The data were recorded using the data acquisition card (model: Advantech USB 4718). For the metallographic preparation, all the samples were mounted, polished using the standard metallographic techniques and etched using Kroll’s reagent (Distilled water-92 ml, nitric acid-6 ml and hydrofluoric acid-2 ml). The width and depth of the molten pool were measured using an Olympus SZ-X16 stereoscopic microscope.

![Diagram of laser welding experiments](image)

Fig 1. Schematic of the laser welding experiments.

### III. NUMERICAL SIMULATION

The purpose of this study was the numerical modeling and experimental investigation of temperature distribution and molten pool dimensions to predict the depth and width of the molten pool and HAZ dimensions. Due to the fact that the workpiece is moving in x direction, the temperature distribution and the melting pool shape are not asymmetric. As a result, the problem is a transient three-dimensional problem. For simplicity, the weld pool surface was considered to be flat and the complex physical phenomenon causing the formation of keyhole was not considered. The governing equations and their boundary conditions were discretized by control volume schemes. The SIMPLE algorithm and first upwind discretization method [5] were used to calculate the fluid flow and heat transfer phenomena.

#### A. Governing equations

The mathematical formulation of the model is based on the following assumptions:

- The initial temperature for workpiece is at 293 K. The laser beam and coordinate system are fixed and workpiece moves in the x direction with a constant velocity. The thermophysical properties of the material are temperature dependent. The equations of continuity, energy and momentum in the Cartesian coordinate system can be written as follows [6]:

**Continuity equation**

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0 \quad (1)$$

**X -momentum equation**

$$\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho uu)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x} \left(\mu \frac{\partial u}{\partial x} + \mu \frac{\partial v}{\partial y} + \mu \frac{\partial w}{\partial z} - \frac{\mu}{K} (u - v_w) \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial u}{\partial y} + \mu \frac{\partial v}{\partial x} + \mu \frac{\partial w}{\partial z} - \frac{\mu}{K} (u - v_w) \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} + \mu \frac{\partial v}{\partial y} + \mu \frac{\partial w}{\partial x} - \frac{\mu}{K} (u - v_w) \right) \quad (2)$$

**Y -momentum equation**

$$\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho vv)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x} \left(\mu \frac{\partial v}{\partial x} + \mu \frac{\partial u}{\partial y} + \mu \frac{\partial w}{\partial z} - \frac{\mu}{K} (u - v_w) \right) + \frac{\partial}{\partial x} \left(\mu \frac{\partial v}{\partial x} + \mu \frac{\partial u}{\partial y} + \mu \frac{\partial w}{\partial z} - \frac{\mu}{K} (u - v_w) \right) + \frac{\partial}{\partial z} \left(\mu \frac{\partial v}{\partial z} + \mu \frac{\partial u}{\partial y} + \mu \frac{\partial w}{\partial x} - \frac{\mu}{K} (u - v_w) \right) \quad (3)$$

**Z -momentum equation**

$$\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho dw)}{\partial z} = -\frac{\partial P}{\partial z} + \frac{\partial}{\partial x} \left(\mu \frac{\partial w}{\partial x} + \mu \frac{\partial u}{\partial z} + \mu \frac{\partial v}{\partial y} - \frac{\mu}{K} (u - v_w) \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial w}{\partial y} + \mu \frac{\partial u}{\partial z} + \mu \frac{\partial v}{\partial x} - \frac{\mu}{K} (u - v_w) \right) + \frac{\partial}{\partial x} \left(\mu \frac{\partial w}{\partial x} + \mu \frac{\partial u}{\partial z} + \mu \frac{\partial v}{\partial y} - \frac{\mu}{K} (u - v_w) \right) \quad (4)$$

**Energy equation**

$$\rho C_v \left(\frac{\partial T}{\partial t} + (u - v_w) \frac{\partial T}{\partial x} + (v - v_w) \frac{\partial T}{\partial y} + (w - v_w) \frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial x} \left(\kappa \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y} \left(\kappa \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z} \left(\kappa \frac{\partial T}{\partial z}\right) \quad (5)$$

In momentum equations, $K$ is the permeability coefficient, which is related to the liquid volume fraction with the Koreny–Carman equation [7]. It enables us to have a smooth transition of velocity from zero in the solid region to a large value in the fully liquid region for the fixed-grid numerical method [8]. In energy equation, according to a suitable latent updating form during each interaction within a time step updated, a source-based method is used to deal with the latent heat of fusion, $\Delta H$, as an additional heat source. By introducing the permeability factor and source-based method, the Eqs. (1)–(5) are unique for both liquid and solid phases. Therefore, it is not necessary to track the melt-solid interface and specify a boundary at that location. In the weld pool, the surface tension force, the Lorentz force and the buoyancy force interact with each other. The Marangoni convection which is the main driving force of the fluid flow, acts because of the temperature dependence of the surface tension [9, 10].

#### B. Boundary and initial conditions

The boundary conditions at the upper surface are as follows

For the weld pool (in the liquid region)

$$\mu \frac{\partial u}{\partial x} = \frac{\partial \gamma}{\partial T} \frac{\partial T}{\partial x}; \quad \mu \frac{\partial v}{\partial y} = \frac{\partial \gamma}{\partial T} \frac{\partial T}{\partial y}; \quad \mu \frac{\partial w}{\partial z} = \frac{\partial \gamma}{\partial T} \frac{\partial T}{\partial z}; \quad w = 0 \quad (6)$$

where $\frac{\partial \gamma}{\partial T}$ is the temperature coefficient of surface tension

For the solid region

$$u = v_{\text{welding}}; \quad v = 0; \quad w = 0 \quad (7)$$
The initial condition at time $t = 0$ is given as
$$T(x, y, z, 0) = 293 \text{ K}$$ \hfill (8)

The convection and radiation boundary conditions on all surfaces are considered. In addition, on the top surface, a transient heat flux (which is produced by the beam laser) is considered [11]

$$-k \frac{\partial T}{\partial z} = q - \varepsilon(T)\sigma(T^4 - T_{\infty}^4) - h(T - T_{\infty})$$ \hfill (9)

where $h$ is the convective heat transfer coefficient, $\sigma$ is Stefan–Boltzmann constant $= 5.67 \times 10^8 \text{ W/m}^2\text{K}^4$ and $\varepsilon$ is emissivity. For radiation and convection problems, the following lumped convection coefficient was used as suggested by Frewin and Scott [4]

$$h = 2.4 \times 10^{-3} \varepsilon T^{1.61}$$ \hfill (10)

### IV. RESULTS AND DISCUSSION

The effect of process parameters on temperature history is investigated in Fig. 2. The temperature histories for specific points (A and B) representing the positions of thermocouples have been plotted. In the experiment corresponding to this figure, the temperature histories of welding process were studied with the variation in the welding speed by keeping the remaining parameters equal to each other. As shown in this figure, the finite volume (FV) thermal model (numerical simulation) was in good agreement with the experimental data. Also, we observed that the temperature histories for different welding speeds had similar trends in the case of identical welding speed. This figure shows that by decreasing the welding speed, the peak value of temperature diagram is increased and its maximum value occurs at a longer time. It can be observed that the temperature histories of both the numerical and experimental data had similar shapes when they were compared.

Fig. 2 Simulated and experimental results of temperature distribution for points A and B as a function of welding speed (a) $v = 3$ mm/s, (b) $v = 6$ mm/s

![Fig. 2 Simulated and experimental results of temperature distribution](image)

Fig. 3 reports the welding width versus welding speed achieved by performing an experimental setup with 25 Hz pulse frequency, 4.2 ms pulse duration and average power of 240 W. The welding speed was varied between 3 and 9 mm/s. According to the results, the width was decreased with increasing laser welding speed. This increase in the welding speed has an inverse effect on the welding width. In laser welding, a good weld is not only a weld with sufficient penetration but also, it is one with an acceptable weld surface (width). Hence from this figure, we can conclude that at sufficient low welding speed, we have a larger width and the weld surface has an acceptable quality.

![Fig. 3 Experimental and numerical results: width versus welding speed variation](image)

Fig. 4 shows the melt pool depth as a function of welding speed. It is clearly seen that the melt pool depth was decreased by increasing the laser welding speed. This means that at a given laser power, a larger welding speed did produce lower penetration depth. It should be noted that the numerical results
agreed with the experimental data.

![Experimental and numerical results: penetration depth versus welding speed variation](image)

**Fig4.** Experimental and numerical results: penetration depth versus welding speed variation

A numerically predicted temperature contour versus the experimental micrograph for welding speed of 3 mm/s is plotted in Fig. 5 for comparison between numerical and experimental results. It can be concluded that the predicted numerical temperature contours give a good insight related to phase transformation in the molten pool and HAZ as observed in Fig. 5.

![The cross sectional area of the sample numerical and experimental results v =3 mm/s](image)

**Fig5.** The cross sectional area of the sample numerical and experimental results $v =3 \text{ mm/s}$

In laser welding different zones are always identified such as the fusion zone (FZ), the heat-affected zone (HAZ), and the base metal (BM). According to the Fig 6, the HAZ microstructure consists of a mixture of martensitic $\alpha'$ and primary $\alpha$. The FZ microstructures are identified as $\alpha'$ martensite. Martensitic phase could be obtained because the welding pool temperature reached the $\beta$ transus (980 °C for Ti6Al4V) and the cooling rate was high.

![Microstructure of the heat-affected zone and fusion zone (FZ)](image)

**Fig6.** Microstructure of the heat-affected zone and fusion zone (FZ)

In this paper a numerical and experimental study of laser welding was conducted for prediction of temperature distribution and molten pool geometry. The variations in the weld geometry (width and depth) that affected by laser welding parameters indirectly estimated with considering the temperature variations around the molten pool which obtained from the numerical model. The finite volume thermal model is in good agreement with the experimental data. The model can predicts the influences of laser welding speed on the weld pool shape and size related to temperature variations. The predicted numerical temperature contours give a good insight related to phase transformation in the molten pool and HAZ.

**REFERENCES**


