Experimental and numerical investigation of temperature distribution and analysis of mechanical properties during pulsed Nd-YAG laser welding of thin Ti6Al4V alloy

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Abstract. Nd: YAG laser welding is an important joining technique for titanium alloys in aerospace industries, aircraft industries, biomedical instrument and various other fusion welding industries. Titanium alloy (Ti-6Al-4V) is used during the research, because it has high strength and oxidation resistance in a wide range of temperatures. It is used in combustion cans, and transition liners in both aircraft and land-based gas turbines and medical engineering. In the present research work, an experimental and numerical analysis of Nd-YAG laser welded titanium alloy thin sheet for temperature distribution has been done. A three dimensional heat conduction equation has been used for the numerical simulation. The influence of different welding conditions like welding speed, welding power on the heat affected zone (HAZ) morphology, metallurgy and mechanical properties was discussed in detail. Microstructures were assessed by optical microscopy and by field emission scanning electron microscope (FE-SEM), while the mechanical behavior was analyzed in terms of Vickers micro-hardness is compared with different welding conditions. The temperature field of the welding process for the different parameters were studied. It was found that the simulated results are in good agreement with the experimental result.

1. Introduction

Presently, Ti–6Al–4V is one of the most widely used titanium alloys, accounting for more than half of all titanium tonnage in the world, and no other titanium alloys threaten its dominant position [1, 2]. It is a two phase α+β alloy, with aluminum as the alpha stabilizer and vanadium as the beta stabilizer. Due to its high strength and low density, along with good tensile and creep properties up to about 300°C, Ti–6Al–4V alloy is widely used for turbine disks, compressor blades, air frame and space capsule structural components, rings for jet engines, pressure vessels, rocket engine cases, helicopter rotor hubs, fasteners, critical forgings requiring high strength-to-weight ratios, medical and surgical devices [3]. This alloy can be strengthened by heat treatment or by thermo mechanical processing. However, the best combination of properties can be obtained by solution heat treatment just under the β-transus temperature (about 985°C), followed by rapid quenching and ageing. Conventionally, TIG, plasma arc [4], and electron beam welding [5] have been used...
to weld titanium alloys. Limited literature on laser welding of Ti–6Al–4V alloy is available and most of the reports have concentrated on CO2 laser [1, 2, 6 and 7]. [4] Compared the parameters and microstructures for TIG, plasma, and CO2 laser welding of 5-mm-thick sheets of Ti–6Al–4V alloy. It was found that for all the welding processes, sufficient shielding protection of the heated weld area (above 400°C) was crucial for producing successful joints. Yang et al. developed a 3-D model for a moving Gaussian laser heat source to analysis the temperature field and the depth of heat affected zone (HAZ). Results shows that the depth of the heat affected zone is largely depends upon the parameters [8]. Pantelis et al. have used Fourier differential equation to validate the experimental data [9]. The effects of welding method, peak temperature, and cooling rate on the susceptibility to intergranular corrosion of 690 alloy welded samples had been studied. It indicates that for the cooling rate around 212.6 °C/s laser beam welding process produced much less mass loss then the gas tungsten arc welding process [10]. Rosenthal had developed a model to a moving heat source for the numerical simulation. Results shows that on varying the parameter the thermal properties can be varied easily [11]. Abderrazak et al. used both experimental as well as finite volume method to investigate the thermal behaviour during continuous laser welding. It has been found that the welding parameters such as welding speed and laser power very much affects the size and shape of the weld bead of the workpiece [12]. Yang et al. worked on a three dimensional finite element model to investigate the microstructural and mechanical changes in the HAZ in the Ti6Al4V thin welded plate using a moving Gaussian laser heat source [13]. Semak et al. study the effect of evaporation recoil pressure on melt flow and the related convective heat transfer using a hydrodynamic physical model. Results show that the convective heat transfer which is induced by recoil pressure is enough for absorbed laser intensities [14].

This study mainly discus on the characterization of the heat affected zone and analysis of mechanical properties generated by Nd-YAG laser welding of thin Ti6Al4V alloy. The HAZ produced by laser welding at varies pulsed laser parameters was analyzed experimentally and validated by numerical simulation.

2. Experimental procedures and material

2.1. Experimental material and its mechanical properties

In the present experiment, the Titanium alloys (Ti-6Al-4V) sheet with a thickness of 1 mm was chosen as welding materials. The chemical composition (wt %) and mechanical properties of the Titanium alloys (Ti-6Al-4V) material were shown in Table 1 and 2 respectively. Figure 1 presents the EDX analysis of the (Ti-6Al-4V) alloy.

Table 1. Chemical composition

| Element | Weight% | Atomic% |
|---------|---------|---------|
| C       | 3.78    | 12.94   |
| Al      | 7.08    | 10.78   |
| Ti      | 85.75   | 73.55   |
| V       | 3.38    | 2.73    |
| Totals  | 100.00  |         |

Fig. 1 EDX Analysis of the titanium alloys sample
Table-2. Mechanical Properties of as received Ti-6Al-4V

| Property                  | Value   |
|---------------------------|---------|
| Tensile strength (N/mm²)  | 964 ±42 |
| Yield strength (MPa)      | 891±39 |
| Elongation (%)            | 14     |
| Hardness (Hv)             | 356    |

2.2. Laser welding setup
This work presents the pulsed Nd-YAG laser welding of thin Ti-6Al-4V alloy sheet. Each sample of size 165 mm×150 mm×1 mm were cut with the help of wire cut EDM machine. Just before the welding process the treatment with mixture of 60% water and 40% concentrated nitric acid were done to remove the oxide layer.

Table-3. Fixed parameter used in the present study

| Parameter                  | Value     |
|---------------------------|-----------|
| Wavelength                | 1.06µm    |
| Maximum average power     | 200W      |
| Pulse energy              | 20J       |
| Peak pulse power          | 1000W     |
| Pulse duration            | 0.5-20ms  |
| Pulse frequency           | 20Hz      |
| Focus diameter            | 0.3-2.2mm |

The 400W Nd: YAG laser welding machine was used to weld the Titanium alloys (Ti-6Al-4V) sheet. The spot diameter of the laser beam was 0.3 mm with a focal length of 190mm. The argon (Ar) was selected as the shielding gas. The flow rate of adding gas was 8L/min in the condition of coaxial adding gas during the Nd: YAG laser welding. The Machine specification has been shown in table 3. For the measurement of the temperature field at different locations, three K-Type chromel–alumel thermocouples each of 1 mm diameter and 200 mm length were fixed perpendicularly at a distances of 4mm from one another away from the weld zone as shown in Fig. 2. The range of thermocouple is 100°C to 1200°C. The first thermocouple were placed at a distance of 4 mm from the weld bead because the chances of melting of thermocouple may occur. A computer system with attached DAQ system were used for acquiring the thermal cycle data of thermocouples. The arrangement of the welding setup has been shown in Figure 2.
In order to obtain the better laser welding quality quickly and use less material, parameters such as laser power \( (P) \), the welding speed \( (v) \) and defocusing distance \( (D_f) \) were chosen to change. The shielding gas was the Argon \( (Ar) \) with the flow rate of 8L/min, the defocusing distance of -3 mm and the laser welding speed was 35mm/s during Nd: YAG laser welding. Table 4 shows the welding parameter used in this work.

2.3. **Measurement of micro-hardness**  
The micro-hardness of the Nd: YAG laser welds was performed by micro-hardness tester (ECONOMENT VH-1MD) using a diamond indenter \( (\text{NO.HV110716}) \) at room temperature. The micro-hardness gauge was HV, the force was 1.961N (200gf), the hold time of the force was 10 second and the surface shape was plane.

2.4. **Tensile test measurement**  
The tensile test specimens were prepared as per the prescribed standard in ASTM E-8.

| Sample | Average power (Watt) | Welding Speed (mm/s.) |
|--------|----------------------|-----------------------|
| a      | 220                  | 8                     |
| b      | 220                  | 10                    |
| c      | 190                  | 8                     |
| d      | 190                  | 10                    |
| e      | 170                  | 8                     |
| f      | 170                  | 10                    |

Fig. 3 Tensile specimen (thickness: 1 mm).

The weld samples contained part of the HAZ with fusion zone at the centre of the Nd: YAG laser weld, as shown in Fig. 3. A fully automated close loop servo mechanical tensile testing machine \([\text{BISS}]\), having load capacity of 25KN, was used. The tensile tests were conducted at room temperature.

3. **Numerical model and simulation**

3.1. **Construction of welding model and meshing**  
Figure 4 (a) shows the geometry of the welding model. Meshing of the model has been shown in Figure 4 (b). A 20-noded 3-D thermal element \( (\text{Solid70}) \) is used. The meshing is very fine in the regions where the Gaussian laser source is incident (i.e. near the welding zone), while a coarse mesh is applied elsewhere. The meshing type is brick meshing. The model contains 47,310 nodes and 104,252 elements.
4. Thermal analysis

4.1. Boundary conditions

Initial condition at time \( t=0 \), \( T(x, y, z, t) = T_0 \)

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.

\[
-k \frac{\partial T}{\partial z} = q - h(T - T_o) - \varepsilon \sigma (T^4 - T_o^4)
\]

Where \( h \) is the convective heat transfer coefficient, \( s \) is Stefan–Boltzmann constant = 5.67108 W/m\(^2\)K\(^4\), \( h = 2.4 \times 10^{-3} \varepsilon T^{1.61} \), \( \varepsilon \) is emissivity. \( \varepsilon = 0.708 \pm 0.012 \) [15]

4.2. Assumptions

- The initial temperature for workpiece is at 300 K.
- The heat source moves in the x-direction with a constant velocity, \( V_{\text{welding}} \).
- The surface of weld pool is smooth and flat.
- All thermo physical properties of the material are varying with temperature.
- During the welding in the weld pool the material flow is incompressible and laminar.

4.3. Heat source

The Gaussian distribution of laser power intensity has been used.

\[
P(x, y, z, t) = P_0 h(t) e^{-\left(\frac{2r^2}{r_b^2}\right)}, \text{ Where } r = \sqrt{x^2 + y^2} \text{ is the distance from the laser beam center [16].}
\]

Where \( r_b \) is the laser beam radius.

\( P_0 \) is the laser intensity at the center of the beam. \( P_0 = \frac{2P_{\text{tot}}}{\pi r_b^2}, P_{\text{tot}} \) is the total absorbed power.

\( P_{\text{tot}} = \eta P_{\text{incident}} \)

\( P_{\text{incident}} \) is the incident laser power. \( \eta \) is the average absorptivity of the workpiece material.

Average absorptivity of Ti6Al4V plate workpiece is 0.34. \( h(t) \) shows the temporal variation of intensity. In the pulsed laser welding, when the pulse is active, the value of \( h(t) \) was 1 and when the pulse is inactive the value of \( h(t) \), was zero.
5. Results and discussion

5.1. Progress of the temperature field

Fig. 5 shows the temperature distribution profile of the weld pool in different time frame. Figure (a) shows the contour plot of the temperature distribution of the flat face of the weld block at a power of 190 watt and 8 mm/sec in 2.56 sec. In this temperature profile the maximum temperature is 3614.9 K and minimum temperature is 300 K. Figure (b) shows the contour plot of the temperature distribution of the flat face of the weld block at a power of 190 watt and 8 mm/sec in 7.5 sec. In this temperature profile the maximum temperature is 3494.8 K and minimum temperature is 306 K. Figure (c) shows the contour plot of the temperature distribution of the flat face of the weld block at a power of 190 watt and 8 mm/sec in 14.25 sec. In this temperature profile the maximum temperature is 3549.6 K and minimum temperature is 298 K. Figure (d) shows the contour plot of the temperature distribution of the flat face of the weld block at a power of 190 watt and 8 mm/sec in 21.59 sec. In this temperature profile the maximum temperature is 3546.6 K and minimum temperature is 299 K. In the contour the temperature profile is axisymmetric about the heat source line. The shape of the contour is almost same in each and every plot.

Fig. 5 Simulated temperature distribution at a power of 190 watt (a) t = 2.56 s. (b) t = 7.5 s. (c) t = 14.25 s. (d) t = 21.59 s.

5.2. Comparison of temperature profile

Fig. 6 shows the experimental and simulated thermal contour profile of all the three thermocouples. Figure (a) shows the comparison between experimental and simulated data at 190 watt and 8 mm/sec. From the graph it is clear that the maximum temperature of experimental thermocouple (K1) is 532 °C and for
simulated thermocouple (K₁) is 521 °C. Figure (b) presents the comparison between experimental and simulated data at 190 watt and 10 mm/sec.

![Fig.6 Experimental and simulation temperature field (a) at 8 mm/sec. (b) at 10 mm/sec.](image)

From the graph it is clear that the maximum temperature of experimental thermocouple (K₁) is 554 °C and for simulated thermocouple (K₁) is 520 °C. It is clear that the deviation of temperature is around 7%. It can thus be concluded that the FEM simulation used in this work is reasonably accurate and can be used for future work.

5.3. **Morphology of the joint**

Figure 7 shows the field emission scanning electron micrograph of the weld bead. Figure (a) indicates the different zone of the weld bead.

![Morphology of the joint](image)
From the image it is clear that the width of the heat affected zone (HAZ) is minimum compare from fusion zone (FZ). Figure (b) presents the microstructure of the base metal (BM). Figure (c) gives the microstructure of the fusion zone. The microstructure consists of large amount of elongated $\alpha$ and the presence $\beta$ lamellae in the inter-granular region. Melting of material by laser led the refinement of the microstructure grains due to different cooling rate at the different area. Due to different cooling rate the normal $\alpha$ changes to elongated $\alpha$. In the FZ some acicular martensite phase was also present. This fine, acicular martensite has a hexagonal closed packed structure and also it has a high hardness but relatively low ductility and toughness. Figure (d) shows the microstructure of the heat affected zone. The microstructure contain some elongated $\alpha$ and some blocky $\alpha$. Blocky $\alpha$ is the $\alpha$ which could not get the sufficient heat to transform into $\beta$ during the transformation.

5.4. Micro-hardness analyses

Fig. 8 presents the distribution of micro-hardness across the laser welding zone. The cross-section of the sample has been divided into three section i.e. upper section (US), Middle section (MS) bottom section (BS). The micro-hardness is maximum in case of upper section and lower hardness is found in middle section.
The micro-hardness of the laser welding zone is higher than that of the base metal, because the alloy elements have no time to form the second phase to precipitate due to the high cooling speed, and these elements dissolve to a great degree, which makes solid solution strengthening occur after the laser welding process. The elongated grains are key reason for the enhancement of the hardness in the Fusion zone.

5.5. Tensile Test
Fig. 9 presents the stress-strain curve of the Nd-YAG laser weld at different welding parameters. The sample were prepared according to the ISO Standard as shown in figure 5. From the graph it is clear that the tensile strength and yield strength is maximum in case of sample A-2. The main reason for the increment of the strength is the high amount of elongated grains in the fusion zone. While the grain size of the base metal also plays an important role in deciding tensile properties of welds. The tensile strength of the base metal is mainly at tribute to the grains. The grain size of the Nd-YAG laser welding zone also plays a major role in deciding tensile properties of welds.

6. Conclusions
Thin Ti–6Al–4V alloy sheets with thicknesses of 1mm were welded using a 400W Nd: YAG laser machine. The effects of welding on surface morphology, microstructures, hardness and tensile properties were investigated at a laser power of 200W.

1. The Vickers micro hardness is higher in the Fusion zone (FZ) than in the HAZ and BM regions. Lowest hardness was found in the base metal region.
2. The presence of elongated grains and regular plate-shaped microstructures and the resultant hardness in Nd: YAG joints are the key factor for the enhancement of the tensile strength of this weld joint.
3. In the fusion zone the elongated grains is maximum and it disappear towards the base metal and HAZ interface.
4. On increasing the Avg. power the heat input increases and that decreases the cooling rate reasonably increases the hardness. After the heat treatment microstructure of the alloys changes and it transforms from α to β phase. This transformation and growth in grain size is the reason for the decrease in tensile strength of the welded structures.

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