Melted Zone Shapes Transformation in Titanium Alloy Welded Using Pulse Wave Laser

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Abstract. The study demonstrates laser welding of titanium alloy Ti6Al4V using middle range power Nd:YAG laser. Butt welding cross section views were analyzed to understand the influence of several scanning parameters to the welding beads shapes and material characteristic changes. Pulse laser was used to perform welding on titanium alloys Ti6Al4V. It was found out that fusion zone can appear in two layers which could give clues to internal temperature distribution during the scanning process.

Introduction

Pulsed mode laser is known to have excellent penetration capability compared to continuous mode laser. The combination between pulse wave and continuous wave laser is able to enhance the welding penetration depth. Comparatively higher peak power delivered by pulse wave laser beam is able to penetrate and makes root-shape structure at the welding interface [1]. The capability of generating extremely high energy concentration in a limited time provides the flexibility in temperature distribution control. However, the high energy density could create explosion which contributes to sputter and dross problem [2]. Steep temperature distribution also could generate internal stress which contributes to distortion, cracks, mechanical properties changes and others welding defect.

On the other hands, titanium alloys are widely used in the area which requires strength and other material properties such as biocompatibility and good corrosion resistance [3, 7]. A lot of study in titanium welding has been reported and proved that laser beam is a reliable heat source for welding purposes. Peak power is reported to be the most important parameter in penetration depth determination while pulse duration increment could increase the penetration depth without increasing the risk of craters generation [2]. However, the thickness of the welded material needs to be considered in determining the peak power value to be used. In the case of thinner material, different heat distribution will generate different results even though they are welded using the same scanning parameters.

A. Squillace et al. successfully perform full penetration welding on 1.6 mm thickness titanium alloy using continuous wave Nd:YAG laser with defocused laser beam [4]. All welds present underfill problem and heat affected zone which influence the welding strength. Welding speed which determines the total heat input per unit area and time brings a lot of influence to welding beads shapes and size. In the case of continuous wave, melted zone depth and width decrease with speed increment [5]. Pulse wave laser will result to unstable welding beads depth and width where the process is a repetition of heating and chilling cycle. Scanning speed shall be determined together with pulse repetition rate to obtain the same total induced energy per unit area and total laser spot overlap area.

This study explains the influence of pulse repetition rate (f_p), pulse width (t_p), average laser power (P_{avg}) and scanning speed (v) to the creation of melted zone (MZ) and heat affected zone (HAZ) of Ti6Al4V. Two focusing position (F_p) were attempted and found out that this parameter gave the most significant influence in obtaining fully penetrated melted zone.

Experimental Works

Experimental Setup. Schematic diagram of specimens and experimental setup is shown in Fig. 1. Maximum average power of 300 W Nd:YAG Laser with focus diameter 0.480 mm and 160 mm focusing distance was used to perform the welding experiment. Argon gas with flow rate 10 l/min was delivered using 6.5 mm inner diameter nozzle with approximately 45 °tilted and 10mm from the scanning point. Titanium alloy (Ti6Al4V) specimens with approximately 1.8 mm thickness, 10 mm width and 25 mm length were irradiated using several parameters shown in Table 1 and Table 2 for 25 mm of straight scanning length. Scanning process was started and ended outside the specimen top surface. Then, specimens were cut perpendicularly to the scanning line 10 to 15 mm from the scanning starting edge and polished for welding beads characteristics analysis.

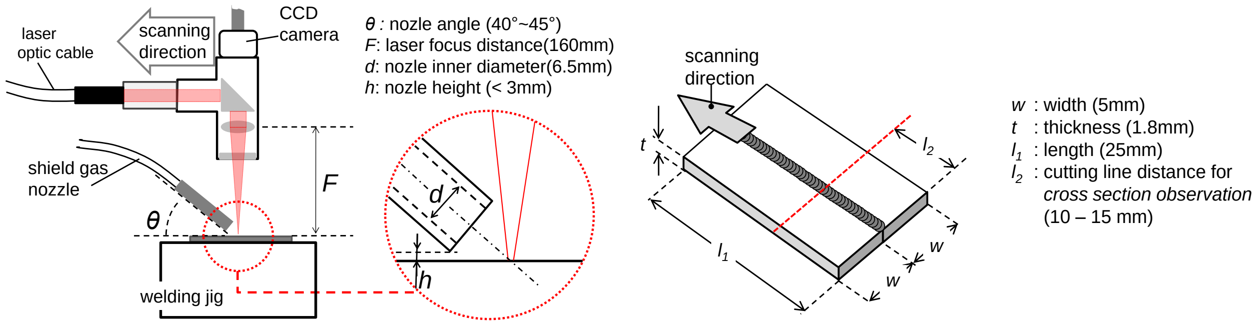

Fig. 1: Experimental setup and work piece schematic diagram

Table 1: Scanning parameters under different scanning speed and pulse repetition rate

Scanning speed v(mm/min)	Pulse width t_p(ms)	Pulse repetition rate /Average laser power f_p(Hz)/ P_{avg}(W)	Energy E(J)
50,100	1.0	20/30, 30/45, 40/60, 50/75	1.5

Table 2: Scanning parameters under different power and pulse repetition rate

Scanning speed v(mm/min)	Pulse width t_p(ms)	Pulse repetition rate /Average laser power f_p(Hz)/ P_{avg}(W)	Energy E(J)
50	0.5, 1.5, 2.5, 3.5	20/30	1.5

Welding Beads Analysis. EDM wire cut was used to cut the specimens for the cross section view observation. Grinding and polishing was done using sand paper (grit 400, 600 and 800) and diamond compound (1, 3 and 9 µm). Etching process carried out to reveal the grain structure before the observation is done using measuring scope with 50X and 200X magnifications. The hardness of welded specimens was measured to observe the mechanical properties changes.

Results and Discussions

Welding Beads Shapes Changes. Under constant laser energy, pulse repetition rate increment does not able to increase melted zone depth (Fig. 2). The melted zones remain in triangle shapes because of the Gaussian's mode laser intensity distribution. However, the melted zone transformed into two layers when the scanning speed decreased.

Fig. 3 shows that the melted zone depth is largely influenced by the pulse width. The melted zone turns from triangle shape to radial shape when the pulse width increased from 0.5 to 3.5 ms under the same laser energy. Increasing the pulse width from 0.5 ms to 3.5 ms under the same laser energy caused the peak power decreased from 3.0 kW to 0.43 kW. This makes the penetration depth decreased gradually. The relation between average laser powers P_{avg}, pulse repetition rate f_p, laser energy E, peak power P_{peak}, and pulse width t_p is shown in equation 1 and 2.

$$P_{avg} = f_p \cdot E \tag{1}$$

$$P_{peak} = \frac{T}{t_p} \cdot P_{avg} \tag{2}$$

Increasing the pulse repetition rate form 20 to 50 Hz under the same laser energy will increase the average power to double and a half. In the case of melted zone in Fig. 2, the peak powers were kept at 1.5 kW. Thus, the penetration depths were still nearly constant. When the scanning speed 50 mm/min, melted zone created in two layers when the average power increased to 60 W and above. This is because the amount of energy induced in a unit area increased and limitation of heat conduction rate has caused the melted zone changed to two layers.

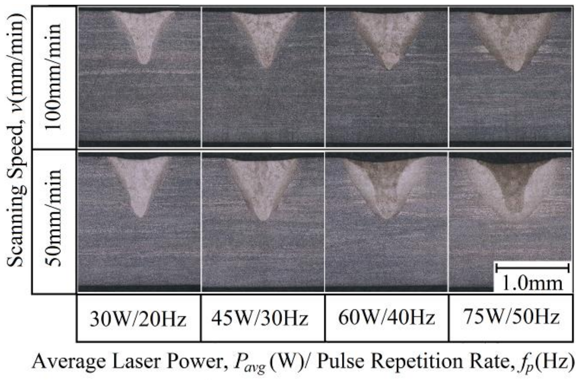

Fig. 2: Melted zone cross section view constructed using different f_p

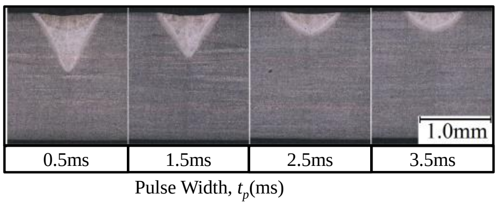

Fig. 3: Butt welding cross section view constructed using different t_p

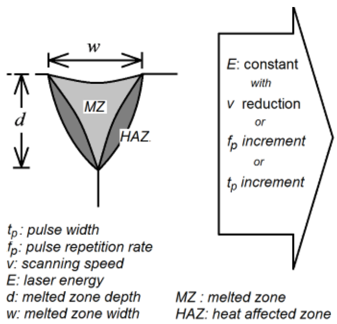

Fig. 4: Schematic diagram of melted zone evolution with scanning parameter changes.

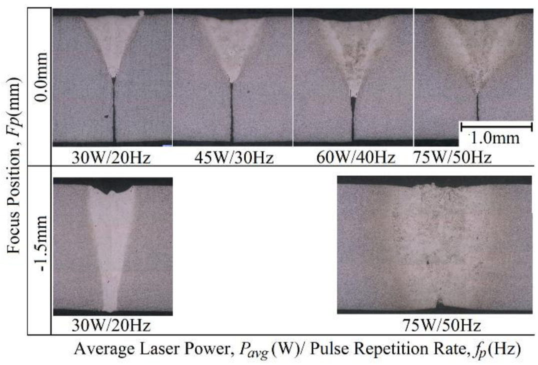

Fig. 5: Melted zone cross section view constructed using different f_p and P_{avg} under constant E (E = 1.5 J, v = 50 mm/min)

The melted zone characteristics transformation is illustrated in Fig. 4. Under constant laser energy output, melted zone shape changes from triangle shape to nearly spherical shape. The melted zone layer divided into two layers under a certain level of induced energy.

To increase the penetration depth, irradiations with different focus point were attempted. The focus point was set 1.5 mm below the specimen surface. The experiment was done in actual butt welding. Fig. 5 compares the melted zone size and shape differences that created under different laser power and focusing depth. It can be seen that under the same laser power and energy, melted zone created deeper and wider when the laser beam focused lower than specimen surface. This is because that the energy is focused more to the inner side and consequently creates deeper welding pool. In the case of focusing the laser on the top surface, most of the plasma generated at the top surface, release heat energy to air via convection and less transferred to welded material. From the point of welding beads appearance, further study on suitable laser energy and peak power need to be done to obtain higher penetration depth without crater defect and less microstructure changes.

Hardness Distribution. The hardness of specimens irradiated under different pulse repetition rate and laser power were measured using Vickers micro hardness measuring machine. Fig. 6 compares the hardness distribution between four different scanning conditions. Measurement was done at position between 0.3 mm and 0.4 mm below the top surface and started from the center of the melted zone in horizontal direction.

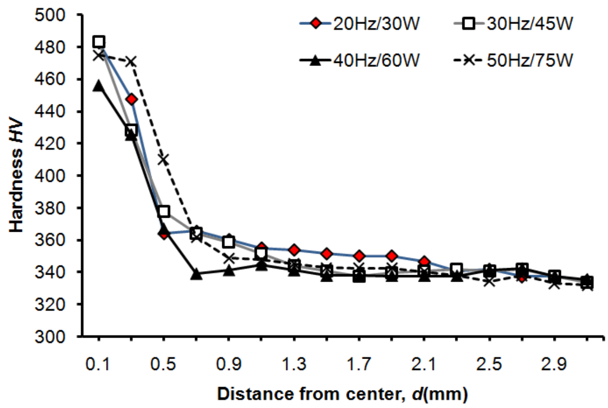

Fig. 6: Comparison of hardness distribution

Significant hardness changes can be seen at the distance, *d* from 0.0 mm to 0.3 mm. This is the area of fusion zone. Heat affected zone (HAZ) exhibits considerable hardness increment and constant hardness values were obtained started from 0.9 mm. However, no significant hardness differences can be seen between two layered fusion zone and single layered fusion zone. The center of melted zones has the approximately same hardness value even though the color after etching is darker when the average laser power used is increased.

In the case of hardness distribution, higher average laser power creates less steep hardness changes compared to lower average laser power. This is because that the HAZ width increases with average laser power.

Microstructure Changes. Excessive laser energy induction onto the same location could generate unnecessary heat which consequently creates two layers of fusion zone. This can be observed from Fig. **7**. For the reason that irradiation using 1.5 J created much craters and sputtering defect, the laser energy used in this experiment was changed to 1.0 J with higher laser power and pulse repetition rate (P_{avg} = 150 W, f_p = 150 Hz). Focus point was 1.5 mm under specimen top surface.

The first layer (a) shows a darker and rough microstructure than the second layer (b). The heat energy transferred via conduction in diametric direction from the irradiated surface. Section "c" is the heat affected zone and "d" is the unmodified area.

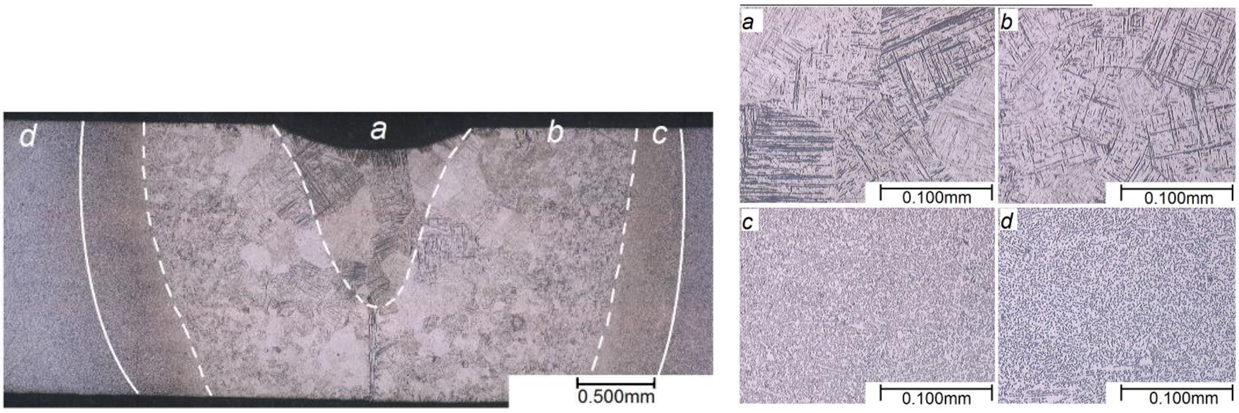

Fig. 7: Welding bead microstructure changes.(t_p = 1.0 ms, E = 1.0 J, f_p = 150 Hz, P_{avg} = 150 W)

First fusion layer (a) is the area which dynamic recrystallisation occurred and remains in β phase. This is the results of temperature increased to far higher than 1600 ℃. In the second layer (b), the length of needle shape structures are shorter because lower maximum temperature achieved during the scanning process. The total time kept above the β-phase transition temperature determines the needle structure length [6]. Third layer (c) identified as HAZ is assumed that the temperature of this area rose up to less than 1600 ℃ but above 1000 ℃. This temperature is just high enough to heat up the material to near melting temperature and trigger phase transition.

Although the fusion zone seems to have successfully penetrated the welded parts, only the first layer of fusion zone is successfully creates weld joint.

Conclusions

Observations have successfully clarified the effect of processing parameters to the welding beads size and shape. Microstructure changes explain the heat transfer behavior which consequently determined the characteristics of melted zone, heat affected zone and defects created during the scanning process.

From the experiment, next conclusions obtained.

a. Increasing average laser power under constant laser energy and peak power is not efficient to increase welding penetration depth.
b. Increasing average laser power and pulse repetition rate could create two layers of melted zone.
c. Pulse repetition rate increment under constant laser energy decreases welding penetration depth.
d. Putting the focus point lower than specimen surface is the most effective method to increase the penetration depth.

In general, none of the parameters used has successfully created full penetrated welding beads with no appearance defect. Further study needs to be carried out to clarify the influence of laser peak energy to the welding penetration depth.

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