Experimental investigations on the effect of heat input on CO₂ laser welded Ti-6Al-4V plates

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Abstract. In this work an attempt is made to study the effect of heat input in CO₂ laser welding of Ti-6Al-4V Plates. Ti-6Al-4V alloys finds wide range of applications in aerospace and biomedical industries owing to their properties such as high strength to weight ratio and very good corrosion resistance. Welding plays an important role in the fabrication of components made of Ti-6Al-4V. In this work, Ti-6Al-4V plates of thickness 3 mm was welded in butt joint position. Laser welding was done at different heat inputs by varying the laser power and keeping the welding speed at a constant value. The quality of the weld was analysed with respect to bead geometry, mechanical properties such as microhardness and Tensile strength. It was understood that, with increase in heat input, mechanical properties got increased. The reasons for the variation of the properties are also discussed with the help of metallurgical analysis.

1. Introduction

Ti-6Al-4V possesses very high strength to weight ratio, high corrosion resistance and good mechanical properties. Owing to these properties, Ti-6Al-4V are extensively used in the field of biomedical and aerospace industries. In aerospace industries, Ti-6Al-4V is mainly preferred in the fabrication of some critical components such as turbine blades of the jet engine, landing gear of aircrafts [1]. Whereas, in biomedical industries, Ti-6Al-4V is mainly used in the fabrication of prosthetic devices such as pacemaker cases, heart valve parts, heart pumps and also in load bearing bones such as hip bones [2]. Ti-6Al-4V alloys are easily weldable and can be welded with different joining processes such as gas tungsten arc welding (GTAW/TIG), plasma arc welding (PAW), Electron beam welding (EBW) and Laser beam welding (LBW) [3]. Among the various welding processes, laser welding process is one of the most preferred welding processes for joining Ti-6Al-4V mainly due to its high energy density, and ability to weld with lesser distortion [4]. Higher energy density causes the temperature gradient to increase drastically in LBW process thereby contributing to the enhanced cooling rate. The cooling rate of the joint is one of the major aspects in any welding process. Cooling rates are dependent on the heat input; higher the heat input, lower is the cooling rate. Kumar et al. [5] performed the fibre laser beam welding of Ti-6Al-4V alloys and reported that the total heat input increased with the increasing average power. Increase in power reduced the weld properties owing to lower cooling rate. Hardness should be given higher importance when the material is used for biomedical applications. Akman et al. [8] investigated the hardness of laser welded Ti-6Al-4V alloys and found that the hardness value in the Fusion Zone (FZ) was higher on comparing with Heat affected zone (HAZ) and base metal hardness.
The authors found that columnar grains formation due to rapid cooling rate increased the FZ hardness. Barreda et al. [6] performed Electron beam welding of Ti-6Al-4V plates using filler metal of similar and different composition to the base metal. The authors observed martensite α’ in the FZ which was formed due to rapid cooling rate. Martensite presence increased the FZ hardness significantly.

T. S. Balasubramanian et al. [7] compared EBM, LBW and TIG welding process for joining Ti-6Al-4V alloy. LBW resulted in better weld properties than the EBM, TIG welded plates. Sabina et al. [11] investigated the tensile strength of the fibre laser welded Ti-6Al-4V alloy. The authors found that tensile strength was reduced by 20% after laser welding, while the elongation percentage of the weld specimen was just 40% of the parent metal. Assessment of weld quality of the fibre laser welded Ti-6Al-4V alloy was performed by Chandan Kumar et al. [12]. The authors concluded that depth of penetration was significantly controlled by the variation in heat input. They further noticed that the presence of blocky α and the martensitic α’ phases at the weld interface improved the hardness and tensile behaviour of the weldments. Kamlesh Kumar et al. [13] studied the microstructure and metallurgical characteristics of the TIG welded Ti-6Al-4V alloys. It was inferred that lower scan speed resulted the FZ with larger grain size and that of higher scan speed resulted in smaller grains. The presence of smaller grains with the transformation of β phase to martensitic α’ enhanced the hardness of the fusion zone as compared to that of the base material.

From the above literatures, it can be inferred that among the various available welding processes, laser welding is preferred for welding Ti-6Al-4V alloys. Mostly fiber laser welding is used for joining Ti-6Al-4V and there are very few literatures related to CO₂ laser welding of Ti-6Al-4V alloys. CO₂ laser welding is more efficient and faster welding process which is readily available and cheaper. Hence, in this work an attempt is made to study the effect to heat input in CO₂ laser welding of Ti-6Al-4V alloys.

2. Experimental Details

Ti-6Al-4V plates of thickness 3 mm were welded in butt joint position using laser power source. 6-axis CNC CO₂ laser welding machine was used to perform the welding operation. Helium gas was used as shielding gas. The welding parameters used in this work are mentioned in Table 1.

| Sample | Power of Laser Beam in (KW) | Speed of welding in (m/min) | Heat Input (J/mm) |
|--------|-----------------------------|----------------------------|------------------|
| A      | 2.6                         | 1.25                       | 124.81           |
| B      | 2.75                        | 1.25                       | 132.02           |
| C      | 2.9                         | 1.25                       | 139.22           |
Chemical composition of Ti-6Al-4V is given Table 2.

| Elements | Ti | Al  | V   | Fe  | Si  | C   | N   | H   | O   |
|----------|----|-----|-----|-----|-----|-----|-----|-----|-----|
| Weight Percentage (%) | Balance | 5.5-6.8 | 3.5-4.5 | <0.3 | <0.15 | <0.04 | <0.015 | <0.15 |

Emery sheets of 600, 1000, 1500 and 2000 SiC grades were utilized for rough polishing and later disc polishing was done using Diamond paste and Hiffin spray. Etching of the samples was done using 88ml of distilled water + 10ml of HNO₃ + 2ml of HF. Macrostructure analysis was done using machine vision system at the magnification of 5X. Microstructure analysis was done using optical microscope at 50X and 100X magnification. Tensile Test was performed by using Universal Testing Machine (UTM) with a gauge length of 50mm and a strain rate of 2 mm/min. After tensile test, the fracture surface of the welded joint was examined using Field Emission Scanning Electron Microscope (FESEM). The hardness test was carried out using Vickers Hardness Tester. Load and dwell time considered for measuring hardness were 500 g and 15 seconds respectively.

3. Results and Discussion
3.1 Effect of Heat Input on the Macrostructure.

Macrostructures of the laser welded Ti-6Al-4V joints are shown in Figure 2.
Figure 2. Macrostructures of the Ti-6Al-4V welded joints with different heat inputs (A) 124.81 J/mm (B) 132.02 J/mm (C) 139.22 J/mm.

The FZ region receives the maximum amount of heat input which results in the change in metallurgical and mechanical characteristics of the weld. Xiao-Long et al. [14] stated that the weld bead can have the following bead shapes, namely V shape, X shape and H shape. The shapes of the weld bead are mainly determined by the welding speed and power. Here, the weld bead is wider at the
top, narrow at the bottom and moderately narrower in the middle and thus it follows an X shaped structure.

It was observed that all the welded samples achieved full penetration, and there is a change in dimension of bead width with change in heat input. As the heat input increased, width of the weld bead increased which is similar to the trend observed in Chao Cheng et al. [15] work.

3.2 Effect of Heat Input on the Microstructure.

The microstructure of the base metal is shown in Figure 3.

![Figure 3. Optical Microstructure of the base metal.](image)
The base metal mainly consists of two phases i.e. globular α and intergranular β. The bright region signifies the β phase and dark region signifies α phase.

The FESEM images of the FZ of Ti-6Al-4V welded joints are depicted in Figure 4.

![Figure 4. FESEM images of the FZ of Ti-6Al-4V welded joints.](image)
As the heat input increases, noticeable microstructural changes were observed in the FZ of the welded joints. Formation of α| martensite in the FZ is visible from the microstructure and this was mainly due to the diffusion less β phase transformation. Depending upon the rate of cooling, a huge amount of β phase is transformed into martensitic α| and massive α in the FZ. It is visible from the Fig. 6 (A, B), at lower heat input (i.e. 124.81 J/mm and 132.02 J/mm) the martensitic α| phase along with massive α and α grain boundary are formed due to higher cooling rate in the FZ region. The formation of massive α in the α| martensitic matrix shows that cooling rate of FZ in the welding condition is nearer to the critical cooling rate which is required for the formation of fully developed α| martensitic structure. At higher heat input of 139.22 J/mm, the rate of cooling is lesser and promotes the broadening of α lamellae’s.

The heat affected zone (HAZ) experiences sufficient heat input for the changes in microstructure without melting. In the current work, the interface between HAZ and FZ is clearly visible from the FESEM analysis, shown in Figure 5.
Figure 6. FESEM images showing interface between HAZ and FZ.

Figure 7(A- near the interface, B- away from interface, C- Nearer to Base metal) shows the FESEM images of the HAZ of the welded joints at different welding power. Small amount of martensitic $\alpha'$ along with original $\alpha$ and original $\beta$ phases are visible from the analysis. HAZ nearer to the interface reached maximum temperature necessary for the formation of $\alpha'$ martensite. Whereas, the region in HAZ that is away from the interface reaches temperature less than $\beta$ transition temperature. Hence, the HAZ away from the interface had only $\alpha$ and $\beta$ phases.
3.3 Effect of Heat Input on Micro-Hardness.

The micro hardness test was performed on Vickers Hardness Testing Machine based on ASTM E38-11 standards. A total of 5 readings were taken in each zone and the average of the measurements are shown in Figure 8. The hardness value of the base metal was found to be 251.47 HV.

**Figure 7.** FESEM images showing the HAZ regions A: near FZ, B: middle HAZ, C: far HAZ of the welded joints.
The hardness values of the welded specimens decreased with the increase in heat input. With increase in heat input, the cooling rate decreased which in turn reduced the formation of α' martensite in fusion zone. In addition to that, the thickness of the α and α' grains became thicker as there was more time for the growth. The hardness values were found to decrease on moving towards the HAZ from the fusion zone. In HAZ, the area near the interface had higher hardness owning to the presence of α'. But the HAZ nearer to the base metal had least hardness value owing to the absence of α'.

3.4 Effect of Heat Input on Tensile Strength.

The tensile test was performed on Universal Testing Machine based on ASTM A370-E8 Standards. All three weld samples got broken in the weld zone indicating weld as the weakest zone. Base metal had tensile strength of 900 MPa with an elongation of 12.7%. The Tensile Strength of the samples A, B and C were found out to be 416.67 N/mm², 401.332 N/mm² and 319.752 N/mm² respectively. It was understood that tensile strength of the welded samples decreased with the increase in the heat input which is similar to the trend followed in Giuseppe Casalino work [16]. The reason attributed to the above trend is, with the increase in heat input, the rate of cooling decreases which increased grains size. The volume of α' martensite also decreased with increase in heat input and the same was observed in the microstructure. These two aspects together contributed to the weld tensile strength. The tensile strength and % elongation of sample A, B and C is displayed in Figure 9. Elongation percentage of all the samples were almost equal but it was very much lower than the base metal.
Figure 9. Stress Strain curve of sample A, B and C.

3.5 Fractography of the Fractured Tensile Sample.
Fractography of the welded samples were studied using FESEM and the fractography of all the welded specimen is presented in the Figure 10 (A, B1, B2, C). The fracture location of all the tensile samples was found in the centre of the welded joint. Fractography of all the welded samples revealed brittle mode of fracture and the same was confirmed by the presence of river markings. Cracks were visible in all three weld samples.
Figure 10. FESEM images of the fractured Tensile Samples with different heat inputs (A) 124.81 J/mm (B) 132.02 J/mm (C) 139.22 J/mm.

4. Conclusion

Ti-6Al-4V plates were successfully welded in butt joint configuration using CO$_2$ Laser Welding process. The properties achieved is more than sufficient for the fabrication of biomedical applications and hence CO$_2$ welding process is recommended for joining Ti-6Al- 4V. Weld showed significant variation in their properties with varying heat input. The major findings from the work are as follows,

- X- Shaped weld bead was seen in all the welding trails. Full penetration was achieved in all the welding trials and a trend of increase in bead width was observed with increase in heat input.
- The phase content of the weld changed drastically with increase in heat input. The $\alpha$ martensite content was more when the heat input was lower and vice versa.
- Hardness was found to be decreasing with increase in heat input. Hardness was controlled by grain size and $\alpha$ martensite. HAZ was found to have least hardness value.
- Tensile test was found to decrease with increase in heat input. All welds revealed brittle mode of fracture.
- In future, Welding should be explored by using different shielding gas compositions in the future work in order to understand its effect on weld properties. In addition to that, works should be done for improving the ductility of the weld.

5. References

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