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Parametric optimisation and microstructural analysis on high power Yb-fibre laser welding of Ti–6Al–4V

J. Ahn [a,*], L. Chen [b], C.M. Davies [a], J.P. Dear [a]

[a] Department of Mechanical Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK
[b] Science and Technology on Power Beam Lab, Beijing Aeronautical Manufacturing Technology Research Institute, China

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ABSTRACT

In this work thin sheets of Ti–6Al–4V were full penetration welded using a 5 kW fibre laser in order to evaluate the effectiveness of high power fibre laser as a welding processing tool for welding Ti–6Al–4V with the requirements of the aircraft industry and to determine the effect of welding parameters including laser power, welding speed and beam focal position on the weld microstructure, bead profile and weld quality. It involved establishing an understanding of the influence of welding parameters on microstructural change, welding defects, and the characteristics of heat affected zone (HAZ) and weld metal (WM) of fibre laser welded joints. The optimum range of welding parameters which produced welds without cracking and porosity were identified. The influence of the welding parameters on the weld joint heterogeneity was characterised by conducting detailed microstructural analysis.

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1. Introduction

The quality and performance of welded joints depend on the weld geometry, melt pool behaviour during welding, the metallurgy of the welded zone and the heat affected zone, and welding defects. The complexity of chemical and metallurgical actions which take place during welding may result in subsequent failure of the weld in service and so, it is important to anticipate and incorporate the effects of welding at the design stage. Around 45% of the causes for welding imperfections is due to poor process conditions [1]. In fact, because the research on the development of welding techniques has been largely conducted to satisfy the needs of the industry for demonstrating the maximum capabilities of a process, many welding fundamentals have not been researched and therefore are not yet fully understood [2]. This means that a significant amount of work is required to be done to be able to predict and optimise the laser welding process to produce consistently quality welds.

In order to obtain an acceptable weld profile and satisfactory mechanical properties, control of weld bead shape is essential as the mechanical properties of welds are affected by the weld bead shape. The weld bead shape which affects the weld metal solidification behaviour is influenced by welding parameters and the corresponding amount of heat input into the workpiece [3]. Therefore, it is necessary to determine the influence of the welding parameters including laser power, welding speed and defocusing distance [4,5] on weld morphology as well as to identify the sources of welding defects. It would then be possible to identify the optimum combination of welding parameters which ensures the required weld quality and properties, and also minimises welding defects [6–8].

This investigation was concerned with the welding parameters including laser power, welding speed and focal distance, and their effects on the weld shape and the final solidification structures of Ti–6Al–4V welds which further influence the overall mechanical properties of the welds. Integrated parametric studies which focus on the influence of various welding parameters on the welding results for fibre laser welding of Ti–6Al–4V have been rarely published. In many cases, even for conventional lasers, investigations have often been conducted case specific with a certain range of process parameters, thus, making it difficult to transfer the results.

Previous studies concerning the effect of welding parameters on weld seam geometry have identified different shapes of laser welds in terms of the top and bottom weld widths. The work of Karlsson et al. [9–13] for example, investigated the influence of laser welding parameters on the weld seam geometry of high strength steels welded with 15 kW fibre laser and it was found that increasing the welding speed can suppress root sagging and undercuts while decreasing the welding speed can suppress lack of penetration. Manonmani et al. [14] studied the effect of laser power, welding speed and beam incidence angle on the weld seam

* Corresponding author.
E-mail address: joseph.ahn08@imperial.ac.uk (J. Ahn).

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geometry in terms of the penetration depth, the bead width and the area of penetration of a 2.5 mm thick AIS1304 stainless steel. They showed that the depth of penetration and penetration area increased with the laser power and the beam angle, whereas, the weld width decreased with increasing welding speed. A trend was observed where the penetration depth and area increased to a maximum value and then decreased with any further increase in welding speed. This was due to the fact that the mode of heat transfer changes from a keyhole mode at lower speeds to a conduction mode at higher speeds.

Different top and root shape classes of laser welded Ti–6Al–4V have been identified in published literature. The centre of the fusion zone as observed by Balasubramanian et al. [15] in CO_2 laser welded Ti–6Al–4V joints, generally presented a convex shape at middle thickness due to volume contraction, surface tension and phase transformation during welding. The specific heat input as mentioned above has a strong impact on the welding bead shape. An increase in welding speed, due to the lower value of specific heat input transmitted to the workpiece, leads to a reduction of the weld width. The heat input was found to be a highly influencing parameter for the bead shape by Squillace et al. [16], who studied the effect of welding parameters on morphology and mechanical properties of fibre laser welded Ti–6Al–4V butt joints. Higher heat input promoted an hour glass shaped weld bead whereas, lower heat input promoted the formation of a V-shaped weld bead. Campanelli et al. investigated fibre laser welding of Ti–6A–4V at a constant power of 1.2 kW and they observed a change in the weld shape from nail head to V-shape when the welding speed was increased from 2 to 2.5 m/min [22]. Mueller et al. [18,19] studied the potential application of CO_2 laser and fibre laser welding of Ti–6Al–4V for aircraft applications and observed a trend where a change in the weld shape from an hourglass shape at low speed to nail head shape at fast speed increase the tendency to entrap gases and form root porosity. The same trend was also observed by Chen et al. [7] in their investigation on CO_2 welding BT20 titanium alloy. Hilton et al. [20] investigated fibre laser welding of 3 and 5 mm thick Ti–6Al–4V and linked the weld profile to porosity level. Low levels of porosity were found in the 5 mm thick weld which used high laser powers. Interestingly, it had a face weld width smaller than the root weld width due to the keyhole behaviour which produced a larger molten volume in the lower part of the weld and promoted the escape of any trapped root shielding gas [20]. The investigation presented in this paper was therefore conducted to determine the influence of key fibre laser welding parameters on the resultant weld quality when welding Ti–6Al–4V, the formation of welding defects and to develop techniques to avoid these issues.

2. Materials and experimental procedures

2.1. Materials

Mill-annealed titanium alloy Ti–6Al–4V (Grade 5) sheets with 2 mm thickness were used with nominal composition given in Table 1. Ti–6Al–4V welds were produced under various welding conditions of laser power, welding speed and focal position. A wide range of processing parameters were tested as illustrated in Table 4, Table 5 and Table 6 in order to maximise the operating window and produce a good weld quality by identifying the optimum combination of laser power, welding speed and focal position. All Ti–6Al–4V welding trials were autogenous.

Table 1
Chemical composition of Ti–6A–4V Grade 5 (wt%).

Ti	Al	V	Fe	O
Balance	5.5 – 6.76	3.5–4.5	0.25	0.2

A 5 kW continuous wave (CW) ytterbium fibre laser was used in TEM01* mode for laser welding as shown in Fig. 1. The beam diameter at focus was 630 µm, the wavelength of fibre laser was 1070 nm, the beam quality factor, M^2 was around 7.3, the divergence half angle of the focused beam was 12.5 mrad and the Rayleigh length for the multimode beam, scaled with the M^2 factor was around 22.6 mm. A beam parameter product (BPP) of less than 2.5 mm mrad was formed. All these parameters influence the focusability and absorptivity of the laser beam.

Industrial grade argon with 99.999% purity was used for welding Ti–6Al–4V. The shielding gas was supplied to protect both top and underside of the weld. The coaxial shielding gas was delivered via the weld nozzle to protect molten pool and the back protecting shield gas was supplied via the shielding gas path in the copper insert to protect back weld. A total shielding of titanium weld seam was provided by the additional trailing shielding shoe with its own shielding gas supply following along behind the laser beam at a distance no more than 2 mm from the surface of the workpiece [22]. Argon was used for back shielding in all experiments at a flow rate of 15–20 l/min. The flow rate for coaxial or side-jet shielding was 20–25 l/min and 25 l/min for drag cover shielding.

Welding was performed parallel to the rolling direction of the Ti–6Al–4V sheets, and followed the recommendations written in the standards ISO/TR 17671-6, AWS C7.2 and BS EN 1011-6 for the control of laser beam welding of metallic materials [23–25]. All the specimens which were used for microstructural analysis were welded bead on plate so there was no requirement for joint fit up or alignment tolerances during weld preparations. The main welding parameters investigated were laser power, welding speed and focal distance.

2.2. Metallographic specimen preparation

Preparation of weld specimens for metallographic examinations was conducted by following the methods specified in the standards, ASTM E3 [26] and BS EN 1321 [27]. Two transverse cross-sections were taken from the welds by electrical discharge machining (EDM) for all welding parameters set, one for examining the weld seam top surface and the other for examining the weld cross-section. The polished specimens were chemically etched for optical microscopy. The microstructural constituents of the weld were revealed by using suitable chemical etchants. The recommended procedure was to use Kroll's reagent which is a mixture of 92% distilled water, 6% HNO_3, 2% HF for etching Ti–6Al–4V specimens by dipping for 15 s [28]. However, such duration was found to be suitable for etching the parent material but not long enough for the weld metal. For this reason, etching was performed for a longer duration in the range of 30–60 s depending on the specimen until the true metallographic weld microstructure of the weld was sufficiently revealed for microstructural analysis.

2.3. Experimental procedures

Experiments were conducted in accordance with the requirements specified in BS EN ISO 15614-11 and BS EN ISO 13919-2 [29,30]. These standards provide guidance on levels of imperfections in electron and laser beam welded joints in metallic materials. The relevant examination and tests for welds in accordance with acceptance level D are listed in Table 2.

As Table 2 shows, visual examination on the welded sheets and metallographic examination on welded specimens were conducted. Since a minimum of one section extracted from the weld is

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