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Experimental investigation and metallographic characterization of fiber laser beam welding of Ti-6Al-4V alloy using response surface method

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ABSTRACT

In the present study, experimental investigations of fiber-laser-beam-welding of 5 mm thick Ti-6Al-4V alloy are carried out based on statistical design of experiments. The relationship between the process parameters such as welding power, welding speed, and defocused position of the laser beam with the output responses such as width of the fusion zone, size of the heat affected zone, and fusion zone area are established in terms of regression models. Also, the most significant process parameters and their optimum ranges are identified and their percentage contributions on output responses are calculated. It is observed that welding power and speed plays the major role for full penetration welding. Also, welding power shows direct effect whereas welding speed shows the inverse effect on the output responses. The bead geometry is influenced by the defocused position of the laser beam due to the change in power density on the workpiece surface. However, overall fusion zone area is unaffected. Mechanical characterization of the welded samples such as microstructural analysis, hardness, and tensile tests are conducted. It is noticed that the hardness value of the FZ is higher than the HAZ and BM zone due to the difference in cooling rate during welding which promotes the formation of α′ martensitic phase in the FZ. Also, an average hardness value in the FZ is compared for two different defocusing positions (i.e. 1 and 2 mm). It is found that hardness value is higher for 1 mm defocused position than 2 mm due the decrement in grain size below a critical range at 2 mm defocused position. The ultimate tensile strength and % elongation of the welded samples are degraded as compared to BM which can be further improved by post heat treatment.

1. Introduction

Titanium and its alloys serve as a bridge between the ideal properties of aluminum and steel. Ti-6Al-4V (Ti64) is a (α + β) phase titanium alloy where aluminum (6 wt%) stabilizes α phase and vanadium (4 wt %) stabilizes β phase. It is widely used in many areas such as aerospace, medicinal, chemical, and aviation industries etc. due of its excellent combination of both strength and ductility, low density, better corrosion resistance and excellent biocompatibility. Generally, Ti64 is thermo-mechanically treated to produce a desired amount of equiaxed α phase having hexagonal closed packed structure (HCP) and intergranular β phase having body centered cubic structure (BCC) with a fine grain size for achieving optimum mechanical properties. The β transition temperature for Ti64 alloy is approximately 995° ± 20 °C. It varies with its composition, presence of interstitial element, and cooling rate [1–3].

Laser beam welding process (LBW) is a nontraditional and advanced welding method for joining similar or dissimilar materials. Nowadays, it is widely used for joining of Ti-6Al-4V alloy where welding defects can be reduced under inert gas atmosphere. Different types of laser heat sources are available for welding purpose i.e. CO_2, Nd: YAG, diode, and recently developed fiber laser. Fiber LBW gained great popularity among all non-conventional welding processes, even to electron beam welding, due to its lower cost. It offers numerous advantages compared to the other lasers such as high efficiency, high beam quality, long life, compact size, and lower operating cost [4–6]. The main features of fiber LBW are high energy density, deep penetration, high flexibility, high precision and narrow heat affected zone etc. There are two different modes of LBW processes based on input heat energy. These are conduction mode (power density < 10^3 W/cm^2) and keyhole mode (power density in the range of 10^5–10^7 W/cm^2). The keyhole mode of welding process allows laser beam to produce welds that are deep and narrow. There are huge number of parameters involved during fiber LBW which affect the weld quality as shown in Fig. 1 [6–9].

The most important fiber LBW input process parameters for controlling welding quality are LBW power, welding speed, defocused

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position of the laser beam, and flow rate of the shielding gas. In past, many researchers studied the LBW process. Kabir et al. investigated the continuous wave 4 kW Nd:YAG LBW of Ti64 plate at different welding speeds and defocusing distances [10]. The crack free weld is obtained at appropriate welding condition. However, some welding defects like underfill and porosity are observed in the weld bead. They also observed microstructural variation from FZ to BMZ due to the difference in the cooling rate. Wang et al. did metallurgical characterization of CO_2 LBW specimens of Ti64 alloy [11]. They reported that needle-like martensitic α' microstructure is formed in the FZ. However, HAZ consists of combination of martensitic α', acicular α, and primary α. The ductility of the welded joint is degraded. However, the ultimate tensile strength is improved due the harder FZ. Squillace et al. investigated the effect of welding speed and laser beam power on the weld quality of 1.6 mm thick Ti64 plate using Nd: YAG laser [12]. The joint quality was characterized in terms of weld morphology, microstructure, and mechanical properties. Cao and Jahazi investigated the effect of welding speed on surface morphology, bead shape, weld defects, microstructure, hardness and tensile properties during welding of 1 and 2 mm thick Ti64 plate using Nd: YAG laser [13]. Minor cracks, porosity and shape defects are observed in the weld bead. The joints showed comparable or marginally higher joint strength. However, significant decrease in ductility is also observed due to the presence of micro pores and inclusions of aluminum oxide. Sun et al. welded 5 mm thick Ti64 alloy and compared bead geometry and microstructure in the FZ for 3 different heat sources i.e. TIG, plasma and CO_2 laser [14]. They found that for all three welding processes, the protection of the bead area is essential for producing successful joints by supplying shielding gas effectively. The depth of penetration, width and hardness of the FZ highly depend on welding speed. Smaller grain size is observed in case of LBW than two other heat sources. Gao et al. investigated the Nd: YAG LBW of Ti64 alloy at different welding conditions and compared the profiles of weld cross section, microstructure and mechanical properties [15]. They observed that H shape weld bead is formed at high heat input and V shape weld bead is formed at lower heat input. The amount of α'martensitic phase is responsible for higher hardness in the FZ and it decreases from FZ to BMZ. The tensile strength of H shaped joint is higher than the V shape joint and the fracture occurred at the interface between HAZ and BMZ. Lisiecki welded two different thicknesses (i.e. 1.5 and 2 mm) of Ti64 alloy plate using high power diode and disk lasers [16]. They reported that the diode laser yields better weld quality than the disk laser. Costa et al. investigated the weldability of the 6.5 mm thick Ti64 alloy plate using fiber laser at different LBW power and welding speed at constant focal position [17]. They reported that the defect-free welds can be achieved by selecting suitable process parameters and effective supply of shielding gas.

Ahn et al. investigated the continuous wave fiber LBW (5 kW) of Ti64 plate having thickness of 2 mm at different LBW power, welding speed and defocusing distance [18]. The joint quality was characterized in terms of weld geometry, microstructure, defects, and hardness. They reported that spatter and undercut is the main welding defect which appears at high LBW power whereas incomplete penetration occurs at low LBW power and high welding speed. Micro pores are also detected within the weld pool and their sizes are in the acceptable range. Nirsanametla et al. did LBW of 3 mm thick 316 stainless steel plate using fiber laser to validate their FEM based heat transfer model [19]. Zhang et al. conducted the deep penetration LBW of 12 mm thick stainless steel with a 10 kW fiber laser. Their experimental results reveal that focal position plays an important role for welding thick plates [20]. Nirsanametla et al. conducted fiber LBW experiments on 5 and 3 mm thick SS 304 and SS 316 plate in open as well in argon gas atmosphere [21]. They concluded that better quality of joint is achieved under argon gas environment. Casalino et al. used fiber laser for joining of 2 mm thick Ti64 alloy plates at different welding conditions [22]. They reported that weld pool contaminations and oxidations can be prevented by providing sufficient amount of shielding gas by adopting a reliable gas supply system. The higher heat input promoted an X-shaped bead, however, lower heat input leads to the formation of a V-shape weld bead. Martensitic phase (which is hard and brittle in natures) and micro pores are formed in the FZ which reduces the strength and ductility of the joint.

The main challenge in LBW of Ti64 alloy is the selection of most significant process parameters and their ranges among various parameters shown in Fig. 1 for achieving better weld quality. Following conventional method of one variable at a time (OVAT) requires a large number of experiments to be carried out which is costly and time consuming. Hence, various soft computing techniques like genetic algorithm (GA), artificial neural network (ANN) and statistical design of experiments (DOE) such as factorial design, Taguchi method and RSM are extensively used to find out the most significant process parameters and their optimum value for achieving better weld quality and also to predict the weld bead geometry, size of the heat affected zone and area of the fusion zones. Acherjee et al. employed RSM to conduct the welding experiments on PMMA sheets considering the LBW power, travel speed, standoff distance, and clamp pressure as an input parameters. Their analysis shows that the interaction effect of LBW power, welding speed and stand-off distance are higher on weld strength and its width [23]. Further it was reported that the optimum welding parameters can be successfully determined using numerical optimization technique. Khorram et al. applied ANN to investigate the effect of LBW power, welding speed, and focal position on butt welded 1.7 mm thick Ti64 workpiece [24]. Their results indicate that welding speed and laser power are the most significant process parameters whereas focal position is insignificant. Anawa and Olabi applied Taguchi approach to optimize the welding parameters for reducing the size of the fusion zone [25]. Their results indicate that laser beam power and speed have strong effect on the area of the fusion zone. However, focal position is not significant for total weld pool size. Sathiya et al. used Taguchi method to relate the LBW input parameters

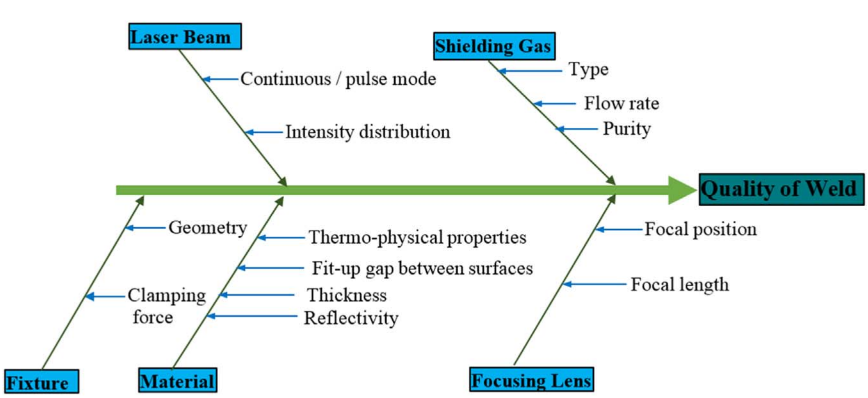

Fig. 1. Fishbone diagram of LBW process parameters.