Journal of Manufacturing Processes 29 (2017) 62–73

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Technical Paper

The effect of Ar and He shielding gas on fibre laser weld shape and microstructure in AA 2024-T3

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ARTICLE INFO

Article history:
Received 12 April 2017
Received in revised form 9 June 2017
Accepted 12 July 2017

Keywords:
Defects
Laser welding
Laser processing
Aluminium
Microstructure
Shielding gas
Argon
Helium
Fibre laser

ABSTRACT

The effect of using argon and helium shielding gas on weld quality, defect formation and microstructure of laser welded aluminium alloy 2024-T3 was investigated. Full penetration autogenous welds were made at a constant laser power of 4.9 kW using a continuous-wave (CW) fibre laser at travel speeds of 3.0–5.0 m/min and focal positions of +4 to −4 mm. To investigate this effect, a comparison was made between Ar and He by examining the weld quality in terms of the face and root weld width, the weld width ratio; and the presence of welding defects including undercut, underfill, reinforcement, porosity and crack. Optical metallography, energy-dispersive X-ray spectroscopy and micro-hardness indentation testing on weld cross-sections were used to identify how the chemical and physical properties of the shielding gases and the characteristics of the fibre laser affect the overall weld geometry. Based on the results, it was believed that relatively small influence of ionisation on fibre laser induced plume enhanced the welding process stability and lowered the threshold power density for keyhole formation. Both Ar and He shielding gases could therefore, be used effectively to produce good quality welds. However, at the lowest speed and also at the maximum focal position, higher ionisation potential and thermal conductivity of helium resulted in an excessive weld width when He was used even though, the overall weld quality was better than that with Ar.

1. Introduction

Aluminium alloy 2024-T3 is a popular material in the aircraft industry due to its light weight, moderate cost and good mechanical properties including specific stiffness, strength and ductility, and good fracture toughness. It is primarily used in fatigue critical structures such as fuselage skin, frames and bulkheads which are under predominantly tension loading conditions. The 2024-T3 alloy with high damage tolerance, has a combination of high fracture toughness, low cycle fatigue strength and resistance to fatigue crack growth and corrosion, making it suitable for fuselage structures, where good static strength, fatigue and fracture resistance are required [1].

Although initially attempts were made to weld AA 2024-T3 aircraft structures, it was determined unweldable by conventional fusion welding processes due to problems related to liquation and solidification cracking and porosity. As a result, it had very limited use for fusion welding applications especially in any stress environment. Fibre laser welds have become attractive alternatives to existing CO_2 and Nd:YAG laser welds due to their higher laser efficiency, superior beam quality, lower maintenance, reduced cooling requirements, smaller footprint and more compact design [2]. While extensive research has been conducted on fibre laser welding of fusion weldable 5xxx, 6xxx and 7xxx series aluminium alloys over the last 20 years, little has been reported on the weldability of AA 2024-T3. The possibility of laser welding AA 2024-T3 would lead to significant cost savings through weight reduction, improved fuel efficiency, lower emissions and manufacturing time compared to riveted structures as well as those welded using the 6000 series alloys currently in use which exhibit lower strength and damage tolerance compared to AA 2024-T3 [3].

Some of the earlier research conducted on laser welding of AA 2024-T3 include partial penetration Nd:YAG laser welding of 13 mm thick AA 2024-T3 in conduction mode by Bardin et al.

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http://dx.doi.org/10.1016/j.jmapro.2017.07.011

[4], autogenous welding of 3 mm thick AA 2024 sheets also using Nd:YAG laser by Hu and Richardson [5], bead on plate welding of 2 mm 2024-T3 in conduction mode using diode laser by Sánchez-Amaya et al. [6] and Yb:YAG disc laser welding of 3.2 mm thick AA 2024 by Alfieri et al. [7] and Caiazzo et al. [8]. In the majority of cases, severe keyhole instability was observed which resulted in poor weld seam quality, porosity formation, cracking and incomplete penetration.

There is very limited research addressing the feasibility of fibre laser welding AA 2024-T3. Janasekaran et al. [9] and Enz et al. [10] studied dissimilar T-joint fibre laser welding of AA 2024 and AA 7075 and showed that single-sided T-joints produced using fibre laser had significantly less macro pores and micro pores than Nd:YAG laser welded AA 6082-AA 5082 and CO_2 laser welded AA 2198-AA 2196 dissimilar joints. Recently, Ahn et al. [11,12] and Chen et al. [13] investigated the effect of varying filler metal feed rate on weld pool chemical composition and the resulting hot crack sensitivity and porosity formation of fibre laser welded 3 mm thick AA 2024-T3. It was found that micro hot cracks and porosities were reduced by diluting the weld pool with less than 0.6% silicon content so that the fraction of Mg_2Si, the solidification temperature and total shrinkage during freezing all decreased.

As fibre laser welding of AA 2024-T3 is relatively untested and unproven, investigations still need to be conducted to study the properties and performance of fibre laser welded AA 2024-T3, optimise the welding procedure and processing parameters to consistently produce high quality welds with no welding defects and with good mechanical properties [11].

Welding in atmospheric conditions can introduce contamination to the weld and lead to reduced effective laser power, keyhole instability and undesired levels of defects. Helium (He) and argon (Ar) inert gases are often used to protect the weld pool from the atmosphere, where Ar is usually the preferred choice because of its lower cost. The composition of the shielding gas affects the heat distribution in the weld, and therefore, controls the weld shape and the welding speed. The increase in welding speed can be economically substantial. In general, the relatively narrow cross section of an Ar shielded weld has a higher potential for gas entrapment and porosity than of He. The extra heat potential of the He can reduce gas entrapment and porosity levels by broadening the weld fusion and penetration [14]. Therefore, the extra cost of the He may be offset by improved quality.

Shielding gas also serves to suppress and blow away laser induced plasma and vapour which partially absorbs, scatters and attenuates the laser energy [15]. Part of the refracted laser beam due to the interaction with vapour plume or plasma prevents the full power density in the incident laser beam from reaching the workpiece and thus, influences the keyhole geometry. Formation of plasma above the keyhole in some aspect, can be considered beneficial as it assists in coupling the beam energy to the weld pool. Heating of the workpiece occurs by significant absorption of beam energy from the keyhole and from the vapour plume above the weld, which releases the absorbed laser energy into the weld near the surface to create a wider face width [16]. The observed weld shapes can therefore, be controlled by the balance between these mechanisms.

The characteristics of the laser induced plasma is related to the wavelength of the laser. Welding aluminium alloys using CO_2 laser with a larger wavelength of 10.6 μm induces strongly ionised plasma with temperatures over 16000 K [15] above the keyhole and partially absorb the laser radiation. On the other hand, near infrared shorter wavelength lasers such as Nd:YAG, disc and fibre lasers (1.07 μm) show lower tendency to form plasma but rather forms less ionised plume of metal vapour and shielding gas within the range of 3000–5000 K as illustrated in Fig. 1.

Table 1
Chemical composition of AA 2024-T3 (Wt.%).

Material	Al	Cu	Mg	Mn	Cr	Si
AA 2024-T3	92.1	5.9	1.0	0.6	0.1	0.3

The inverse Bremsstrahlung absorption of the laser beam in the vapour plume is proportional to the square of the laser wavelength so the absorption coefficient of fibre laser is almost 100 times less than CO_2 laser [17]. Therefore, the vapour plume is either non-ionised or in extreme cases, only weakly ionised in these lasers, whereas, the vapour ionises to form plasma in CO_2 laser. The plume is mainly composed of vaporised metal atoms and metal ions that are ejected from the keyhole but not ionised shielding gases. Due to the apparent absence of significant plasma with fibre laser, the plasma shielding effect is small so beam attenuation and scattering, and the widening of the beam intensity distribution is reduced.

Uspenskiy et al. [18] conducted spectral analysis of vapour plumed formed during 10 kW high power fibre laser welding 6 mm Ti-VT-23 titanium alloy and detected around 3 cm high vapour plume forming on the surface of the workpiece. The vapour plume was only weakly ionised and so the absorbed radiation was negligible of less than 1. Kawahito et al. [14] found that the plume induced when fibre laser welding stainless steel at 10 kW was not significant enough to influence penetration depth. Gao et al. [19] on the other hand, studied the effect of laser power on the characteristics of fibre laser induced plume via emission spectroscopic analysis and found that a strong plasma shielding effect dominated by inverse bremsstrahlung absorption appeared when a laser power greater than 5 kW was used. The relatively small influence of ionisation on fibre laser induced plume was expected to enhance the welding process stability and lower the threshold power density for keyhole formation because of the enhanced Fresnel absorption and reduced beam attenuation and scattering. Katayama et al. [20] investigated the behaviour of laser induced plume or plasma and compared their interaction between CO_2 and fibre laser for welding austenitic stainless steel and aluminium alloy. They found that shielding gas had a greater effect on plasma formation in the case of CO_2 lasers, whereas, the shielding gas effect was less with Nd:YAG and fibre laser.

In this investigation, a series of laser welding experiments was performed to evaluate the influence of Ar and He on the weldability and morphology of high power, continuous-wave Yb-fibre laser welds. The first set compared the difference between using Ar and He shielding gases as a function of welding speed and the second set as a function of focal position. The resulting welds were characterised using optical metallography, energy-dispersive X-ray spectroscopy (EDX) and micro-hardness indentation.

2. Material and methods

Heat treatable aluminium alloy (Al-Cu-Mg) alloy 2024 sheets in the T3 temper condition (i.e. solution heat-treated, cold worked and naturally aged) of 3 mm thickness were used. The chemical compositions of AA 2024-T3 are listed in Table 1.

Beat on plate welding was performed using a 5 kW continuous wave (CW) ytterbium fibre laser system YLS-5000 from IPG Photonics operating in TEM_{01^*} mode at 1070 nm wavelength. The beam had a beam quality factor (M^2) of 7.3, divergence half angle of the focused beam of 12.5 mrad and Rayleigh length of 3.1 mm. The focal length of focusing lens was 300 mm, and the diameter of the focusing lens was 50 mm. The focal length of the collimator lens was 100 mm and the diameter of the collimator lens was 50 mm. The beam diameter at focus was 630 μm and a beam parameter product (BPP) of less than 2.5 mm-mrad was formed. A schematic of the welding setup is shown in Fig. 2.