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Double-sided laser beam welded T-joints for aluminum-lithium alloy aircraft fuselage panels: Effects of filler elements on microstructure and mechanical properties

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ABSTRACT

In the current work, T-joints consisting of 2.0 mm thick 2060-T8/2099-T83 aluminum-lithium alloys for aircraft fuselage panels have been fabricated by double-sided fiber laser beam welding with different filler wires. A new type wire CW3 (Al-6.2Cu-5.4Si) was studied and compared with conventional wire AA4047 (Al-12Si) mainly on microstructure and mechanical properties. It was found that the main combined function of Al-6.2%Cu-5.4%Si in CW3 resulted in considerable improvements especially on intergranular strength, hot cracking susceptibility and hoop tensile properties. Typical non-dendritic equiaxed zone (EQZ) was observed along welds' fusion boundary. Hot cracks and fractures during the load were always located within the EQZ, however, this typical zone could be restrained by CW3, effectively. Furthermore, changing of the main intergranular precipitated phase within the EQZ from T phase by AA4047 to T_2 phase by CW3 also resulted in developments on microscopic intergranular reinforcement and macroscopic hoop tensile properties. In addition, bridging caused by richer substructure dendrites within CW3 weld's columnar zone resulted in much lower hot cracking susceptibility of the whole weld than AA4047.

1. Introduction

Riveting has been the dominant joining technology for aircraft fuselage since decades [1]. The main disadvantages of the riveting process are the low efficiency and high cost. Moreover, it is an extensively researched mature technology in which it is difficult to make further improvements [2–4]. Driven by improving those limitations, double-sided fiber laser beam welding (LBW) technology was first proposed within Airbus Germany to substitute the riveting for joining skin-stringer T-joints and has already been an established process for aircraft manufacturing which offers further weight savings by replacing the riveted differential structure by a welded integral structure [5–7].

In recent years, Al-Li alloys with remarkable advantages such as decreased density, increased elastic modulus as well as appreciable improvement of specific strength and stiffness, have been considered as desirable substitutes for traditional 2xxx and 7xxx series high-strength Al alloys and considerable efforts have been made toward the development of this family [8–10]. In addition, studies involving the weld development of Al-Li alloys have shown a tendency for the formation of a band of equiaxed grains along the fusion line of the weld metal [11–15]. Non-dendritic equiaxed zone (EQZ) forms in a narrow molten region between the partially melted zone (PMZ) and the fusion zone (FZ) [16]. Fine equiaxed grains surrounded by grain boundary eutectic constituents weaken the EQZ and lead to poor mechanical and corrosion properties, consequently, this zone is an important region that requires greater attention [17,18]. Filler material components play an important role in the formation and presence of the EQZ. Furthermore, relative studies have found that the width of the EQZ varies with an increase in Li and Zr content in the filler metal [19].

In our preliminary studies, since Al-Li alloys tended to develop metallurgical induced cracks in the weld seam, the T-joint had to be welded with an additional filler wire which has a high Si-content to avoid the crack formation [20]. Jan et al. [21] studied the influence of the filler elements on the solidification cracking susceptibility in CO_2 laser welding of alloy 2195 using different filler wires, respectively were Al-Si, Al-Mg and Al-Cu alloy wires, and the Al-Si wire was found to be effective on reducing the susceptibility to solidification cracking. In double-sided LBW Al-Li alloys, however, relative simulation results of Zain-ul-abdein et al. [22]

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showed that the post-weld residual tensile stress within T-joint was much more serious than that within previous butt-joint. What's worse, solute segregation occurred and eutectic liquids largely existed along the grain boundaries in the weld due to non-equilibrium solidification during welding. Tian et al. [23] also found that hot cracking still could not be restrained very well even by using AA4047 when double-sided LBW Al-Li 2196/2198 T-joints. In addition, properties of the EQZ had shown considerable influence on T-joints' tensile strengths and fracture characteristics. Most fracture surfaces located in the EQZ showed intergranular mode. All in all, the constituents and proportion of eutectic phases on grain boundaries shows intimate connection with T-joints' tensile properties and hot cracking. New other filler metals with better reinforcement and lower cracking sensibility need to be studied.

Keeping these factors in mind, the current research aimed to study microstructure characteristics of the EQZ and hot cracking defects influenced by chemical composition of filler metals. It would be worthwhile to study the effects of filler chemistry on the EQZ and hot cracking formation, especially with Si and Cu additions. To compared with AA4047, a new CW3 (Al-6.2Cu-5.4Si) wire was firstly studied to successfully enhance the EQZ's properties and restrain hot cracks on T-joints composed of Al-Li alloys 2060 and 2099. Previous studies reported by Zhang et al. [24] and An et al. [25] demonstrated that Al-Li 2060 was very sensitive to hot cracking in LBW butt joints, which could be eliminated by adding appropriate filler wire during welding, and the EQZ was detected along the fusion boundary. In addition, with similar elementary composition of Al-Li alloys 2060 and 2099, Al-Li alloys 2198 and 2196 has also been used for the skin and stringer components and welded by double-sided LBW technology. Tian et al. [23] attempted to develop a hot cracking model through adapting an existing model developed by Rappaz, Drezet and Gremaud for prediction of cracking during casting. The simulation results clearly predicted that the population of cracks increases with increasing laser power. This developed model was capable of accurately predicting the thermal field around the weld and the trend of hot cracking susceptibility as a function of process parameters, however, its accuracy was easy to be influenced by other complex phenomena, like porosity, that was not included in the modeling framework. Since limited public papers about characteristics of the EQZ and hot cracking on double-sided LBW Al-Li alloys T-joints can be found, our work will provide meaningful results especially on double-sided LBW of new 3rd generation commercial Al-Li alloys for aircraft fuselage manufacturing.

2. Experimental procedure

2.1. Materials

In this study, laminated panels (500 mm × 100 mm) of 2.0 mm thick Al-Li 2060-T8 and extruded profiles (500 mm × 28 mm) of 2.0 mm thick Al-Li 2099-T83 were used for the skin and stringer components welding, respectively. The ratios of Cu/Li in these two wrought Al-Li alloys were totally different and they were developed for the aircraft industry by Alcan Inc., in particular for the lower shell fuselage applications. Chemical compositions are shown in Table 1. Due to the choice of alloy and temper condition the stringer material possessed a higher strength than the skin material. This aspect was essential for the stiffening of the final fuselage structure. The average ultimate tensile strengths of Al-Li 2060 and 2099 alloys were 501 MPa and 573 MPa, respectively. Two Filler wires with a same diameter of 1.2 mm were used. One was the eutectic alloy AA4047 manufactured by Maxel Inc, and the other one was a new developed CW3 (Al-6.2%Cu-5.4%Si), as shown in Table 2. Small quantities of Mn and Ti were also introduced via CW3 to refine weld solidification more effectively.

2.2. Experimental method and setup

The double-sided LBW of the T-joint was performed using a combiner of two 10 kW fiber lasers (YLS-10000, IPG Photonics Corp., Germany) and two wire feeders (KD-4010, Fronius International GmbH, Austria), which were controlled by two 6-axis industrial robots (KR-16W, KUKA Robot Group, Germany). The fiber lasers with an emission wavelength of 1.06 μm can deliver in continuous wave (CW) mode. The laser beam passed through a focusing mirror of 192 mm focus length and was finally focused as a spot of 0.26 mm in diameter.

During the double-sided LBW, the weld seams between the stringer and the skin panel were made simultaneously from both sides of the stringer. To achieve a common weld molten pool, the two fiber laser beams should be focused symmetrically onto two opposite positions along the stringer, respectively. To stabilize the welding process, the filler wire and shielding gas were delivered on the same plane as the laser beam and held at an angle of approximately 20° to the stringer. The laser welding facility and schematic diagrams are shown in Fig. 1. The welding parameters used are summarized in Table 3. No heat treatment was carried out on the welded T-joints post welding.

2.3. Macro- and microstructure analysis

After welding, welds' surface appearance and inner metallographic structure were detected by two kinds of optical microscopes (OLYMPUS SZX12 and OLYMPUS GX71). Porosity defects of the welds were tested by X-ray nondestructive testing (NDT) with a range of 200 mm and an angle of 45° between the skin panel and X-ray path. Selected unetched microsections were further examined by a scanning electron microscope (SEM, HITACHI S-3400N) to investigate interfacial structure, fractographic feature, element segregation and hot cracking within T-joints. By the use of a detector fixed on SEM, energy-dispersive X-ray spectroscopy (EDX) analyses were conducted especially on grain boundaries to determine the chemical constituents (except Li) of different eutectic phases. In order to clarify the differences on sort and proportion of eutectic and precipitated phases between these two kinds of T-joints welded by AA4047 and CW3, X-ray diffraction (XRD) experiments were carried out on the weld region using a BRUKER D8 ADVANCE apparatus. In addition, specimens shaped of $1.5 \times 1.5 \times 1.5\ mm^3$ cubic were cut in the centre of the welds and subjected to differential scanning calorimetry (DSC) analysis using a NETZSCH STA 449 F3 (1500 °C) facility, scanning from room temperature to 700 °C at a heating rate of 10 °C/min.

2.4. Hoop tensile testing

Hoop tensile tests in air at room temperature were performed at a strain rate of 2 mm/min using an INSTRON-5569 universal testing machine operated in displacement control. According to ASTM E 8M-04 standard, dog-bone tensile specimens were extracted from the T-joints in TL direction (normal to the welding direction) by electrical-discharge machining, as shown more detailed in Fig. 2. An extensometer with a gauge length of 25 mm was used to measure the strain during the test. The yield strength (YS) ultimate tensile strength (UTS) and ductility (percent elongation) were evaluated.