Journal of Alloys and Compounds 756 (2018) 145–162

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

Nano-indentation investigation on the local softening of equiaxed zone in 2060-T8/2099-T83 aluminum-lithium alloys T-joints welded by double-sided laser beam welding

Bing Han [a, *], Yanbin Chen [a, **], Wang Tao [a], Zhenglong Lei [a], Hao Li [b], Shu Guo [c], Peng Li [a]

[a] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin, 150001, China
[b] National Engineering Research Center of Commercial Aircraft Manufacturing, Commercial Aircraft Corporation of China, Shanghai, 200436, China
[c] Analysis and Measurement Center, Harbin Institute of Technology, Harbin, 150001, China

ARTICLE INFO

Article history:
Received 2 January 2018
Received in revised form
26 April 2018
Accepted 2 May 2018
Available online 5 May 2018

Keywords:
Aluminum-lithium alloys
Double-sided laser beam welding
Equiaxed zone
Local softening
Nano-indentation
Transmission electron microscopy

ABSTRACT

Double-sided laser beam welding of 2-mm-thick 2060-T8 and 2099-T83 aluminum-lithium alloys T-joint was performed with AlSi12 wire. Microstructure and nano-indentation hardness characteristics were studied especially in nondendritic equiaxed zone (EQZ). In comparison with the precipitates of LiAlSi, Mg_2Si and Al_2Cu in weld zone except for the EQZ, an AlCuFeMn icosahedral quasicrystal was detected in the EQZ and Al_3Zr particle could be the heteromorphic core of this quasicrystal phase. Local softening problem was confirmed in the EQZ's localized enrichment regions by nano-indentation tests. The cross sections of different indents in and out of the EQZ's local softening area prepared by focused ion beam (FIB) were examined by using transmission electron microscopy (TEM). For the first time, it was directly observed that an intergranular tiny hot crack was formed right underneath the indent tip in the EQZ's local softening area, and mainly thin Al_2Cu precipitates were generated and sparsely distributed in equiaxed grains and their boundaries. However, thick and continuous Al_2Cu intergranular precipitates with no microcrack defect were observed below the indent in the other area in the EQZ without softening. Obviously, local softening in the EQZ was most likely to be induced by a combined action of the formation of microcrack and the absence of abundant Al_2Cu precipitates in equiaxed grain boundaries. Since the quantity and size of Al_3Zr particle were both much smaller than those of Al_2Cu, it had more limited impact on the EQZ's local softening than Al_2Cu particle in equiaxed grain.

1. Introduction

The third-generation of aluminum-lithium (Al-Li) alloys have been promising candidates for components of aircrafts due to their excellent comprehensive properties such as lower density, higher specific strength and stiffness to weight ratio, and more desirable fatigue and damage tolerance as compared to other traditional aluminum alloys [1–4]. The new 2060 and 2099 Al-Li alloys have been chosen as the materials of fuselage panel components in the production of the C919 (the first China-made large passenger aircraft).

The development of traditional riveting method has come to a status that requires high efforts to continue the progress of increasing production efficiency and aircraft weight savings [5–7]. While, double-sided laser beam welding (LBW) of stringer to skin-sheets instead of using the dominant riveting has promised significant effects on enhancing aircraft manufacturing efficiency and reducing weight [7–10].

For the past few years, many studies have been conducted on double-sided LBW Al alloys T-joints, and excellent weldability of many Al-Cu-Mg 2xxx and Al-Mg-Si 6xxx series combinations has been achieved [11–13]. Dittrich et al. [11] comparatively studied the double-sided LBW characteristics of T-joints composed of 2139 alloys in different heat treatment conditions and found that both the hoop tensile and longitudinal tensile properties of 2139-T3/2139-T8 T-joint were dramatically higher than those of 2139-T3/2139-T3 T-joint. Yang et al. [12] systematically researched the failure behaviors of double-sided LBW 6156-T6/6056-T4 T-joints in head and hoop tensile tests and proposed that the specimens were all fractured along the fusion line between the weld zone and base metal during these two different tensile loading.

---

* Corresponding author.
** Corresponding author.
E-mail address: dabingzhenniu@163.com (B. Han).

https://doi.org/10.1016/j.jallcom.2018.05.014
0925-8388/© 2018 Elsevier B.V. All rights reserved.

In recent years, with the application of new Al-Li alloys in double-sided LBW, however, the microstructural and mechanical features have been changed significantly. Dittrich et al. [11] simultaneously found that not only quantity but also diameter of the weld pore in Al-Li 2198/6xxx T-joint were consistently larger than those in 2139/2139 T-joint. Enz et al. [9] investigated the local chemical composition in 2196-T8/2198-T3 T-joint and proposed that the inhomogeneous distribution of Li in the weld zone likely resulted in local hardness and strength differences, and the local lack of Si could deteriorate hot cracking resulting in mechanical degradation of the weld. In our previous works, a special non-dendritic equiaxed zone (EQZ) with fluctuant width was distinguished beside the fusion line in the weld zone in Al-Li alloys T-joints and butt joints, and softening phenomenon was detected in the EQZ by microhardness test [10,14–16]. Gutierrez et al. [17,18] proposed that fine equiaxed grains in the EQZ were believed to form via a heterogeneous nucleation mechanism aided by Al_3Zr and $Al_3(Li, Zr)$ precipitates. Dev et al. [19] studied the characteristics within the EQZ by Charpy and corrosion tests, and found that relatively poor notch toughness and high intercrystalline corrosion sensitivity were detected in the EQZ and severe grain boundary attack was mainly caused by microsegregation of solute elements Cu, Zn, Mg and the persistence of liquid films at grain boundaries. Fu et al. [20] studied the microstructure characteristic and fracture behavior of laser beam welded 2A97 Al-Li alloy butt-joint, and pointed out that the fracture firstly initiated in the EQZ and the morphology was characterized by intergranular fracture. Ning et al. [21] also studied the fracture mechanism of laser beam welded 2A97 Al-Li alloy butt-joint in quasi-static loading and fatigue tensile tests by high-speed imaging, and found that the crack could rapidly expand to the EQZ in quasi-static tensile tests, and also the crack propagated rapidly to the EQZ in fatigue tensile tests.

Up to now, mechanical degradation in the EQZ has been found not only in Al-Li alloys T-joints but also in Al-Li alloys butt-joints, and most of relevant literatures have describe the fracture characteristic within the EQZ without further mechanism analysis. Since limited research results and literatures about weakening mechanism of the EQZ are announced, further and more detailed investigation is still meaningful to be conducted. A special weakening behavior in the EQZ named local softening has been found in our current research. The purpose of present work is to study microstructure characteristics and local softening mechanism in the EQZ on the double-sided LBW 2060-T8/2099-T83 T-joints.

2. Experimental procedures

2.1. Materials and experimental setup

In this work, the T-joint was composed of 2.0 mm thick Al-Li 2060-T8 laminated panels (600 mm × 150 mm) and 2.0 mm thick Al-Li 2099-T83 extruded profiles (600 mm × 28 mm). A commercially available ER4047 (AlSi12) filler wire with a diameter of 1.2 mm was also adopted in welding process. The chemical compositions of two base metals (BMs) and ER4047 wire are listed in Table 1.

Double-sided LBW experiment was carried out using a welding system consisted of two 10 kW fiber lasers (YLS-10000, IPG Photonics Corp., Germany), two 6-axis industrial robots (KR-16W, KUKA Robot Group, Germany), two wire feeders (KD-4010, Fronius International GmbH, Austria). Two sets of fiber laser and wire feeder were assembled onto two robots respectively and were positioned symmetrically on both sides of the stringer, as shown in Fig. 1. The fiber laser beam with a wavelength of 1.07 μm passed through a focusing mirror with a focal length of 192 mm and the beam diameter in focus position was 0.26 mm. The laser beam was used in continuous wave (CW) mode. The optimized welding parameters were laser power of 3.0 kW, welding velocity of 10.0 m/min, wire feeding rate of 4.3 m/min, filler wire's stick out of 8 mm and shielding gas flow rate of 15 L/min. Above optimized welding were derived from previous numerous experimental results [15,16]. Before welding, the surfaces of the stringer and skin materials were all prepared orderly by chemical cleaning, swashing in fresh water and finally drying in a drying case to get rid of oxidation film, oil stain and coated aluminum.

Table 1
Chemical compositions of two base metals and ER4047 wire.

Alloys	Elements (wt%)									
	Cu	Si	Li	Zn	Mg	Mn	Zr	Ag	Fe	Al
2060	3.9	0.02	0.8	0.32	0.7	0.29	0.1	0.34	0.02	Bal.
2099	2.52	–	1.87	1.19	0.497	0.309	0.082	–	–	Bal.
4047	<0.01	11.52	–	0.001	0.01	0.01	–	–	0.2	Bal.

2.2. Microstructural analysis

Specimens for optical microscopy (OM, OLYMPUS-GX71),

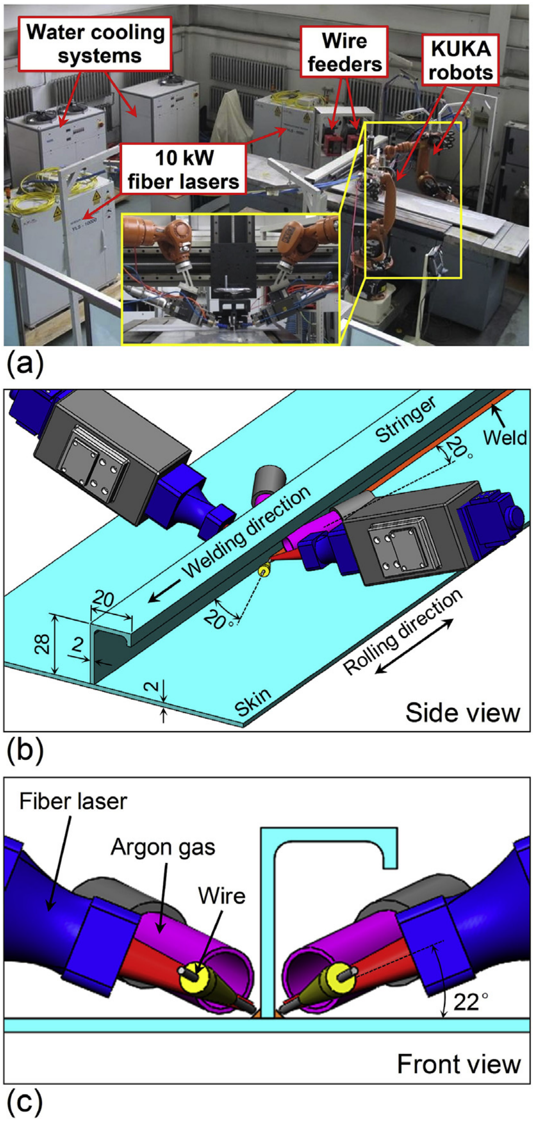

Fig. 1. (a) Laser welding system, (b) and (c) schematics of double-sided laser beam welding process and angle parameters (unit: mm, degree).