Influence of Welding Parameters on Weld Formation and Microstructure of Fiber Laser Beams Welded T-Joint of Aluminium Lithium Alloy

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Abstract. This paper focused on the welding 1.2 mm thick 2A97 aluminium lithium (Al-Li) alloy plates in T-joint form using fiber laser with ER2319 aluminium filler wire. The effects of welding parameters on the T-joint weld appearance, microstructure and the joint mechanical properties were studied systematically, and the influence of welding parameters including the incident beam position and the incident beam angle. The weld shape, microstructure, hardness of the joint were evaluated by optical microscope and micro-hardness test. A uniaxial tensile test was conducted to obtain the tensile property of welded joints. At the optimized parameters, the welded T-joints showed good weld shape without macro defect. The significant softening occurred at the weld zone of the T-joints, and the micro-hardness of the weld ranged from 70 to 85 HV0.2. The tensile strength was about 432 MPa, and the fracture mode of tensile specimens of T-joints was mixed.

1. Introduction
To meet the future demands of the aerospace industry with respect to safety, productivity, weight and cost, new materials and joining concepts have been developed. The recently developed aluminum lithium (Al-Li) alloy 2A97 is very promising high strength and lightweight alloys for aircraft manufacturing, due to its low density, high specific strength and specific stiffness[1], for example, the skin-stringer T-joints for fuselage panels[2, 3]. The modern aircraft manufacturing has adopted the LBW of skin-stringer structures due to the weight savings advantage by replacing the traditional riveted differential structure by an integral welded component[4]. In addition, double-sided laser beam welding of skin-stringer joints was first introduced in Germany[5, 6]. This process was first used in the production of the Airbus A318 and proved to be a promising technology for both improving production efficiency and reducing the weight of modern aircraft[6-8].

However, Laser beam welding for the Al-Li alloy skin–stringer joints were macroscopically demonstrated in few studies investigating the characteristics of this joining technique[9–11]. Schumacher et al. [12]pointed out that the incident beam position was an important parameter and had great impact on joint quality. Al–Mg–Si alloys are particularly susceptible to hot cracking. Therefore, aluminium filler wire containing excess silicon is recommended for 6xxx series alloys[13, 14]. According to Davis, the crack sensitivity decreased remarkably if the Silicon content exceeded 1.5%
Laser beam welding of aluminium alloys minimizes the heat input. However, the loss of alloying elements from the heat affected zone reduces the hardness and tensile strength of the joints[16, 17]. In double-sided laser beam welding of T-joints the incident beam position and incident beam angle are the most important welding parameters. In the present work, the effects of these typical parameters on the welded T-joints morphology are studied in details. The micro-structural features and mechanical properties of Al-Li 2A97 alloys welded T-joints are also identified.

2. Experimental procedure

2.1. Materials
The sheets of aluminium lithium (Al-Li) alloy 2A97 in the T3 temper condition with a thickness of 1.2 mm were used in this study. The dimensions of the skin and the stringer of the T-joints were 300 mm×200 mm and 300 mm×20 mm, respectively. An ER 2319 filler wire with a diameter of 1.2 mm was used. The sheets were chemically milled to remove the surface layer about 0.1 mm from each side before welding to eliminate grease and oxidation film. The chemical compositions of the Al-Li alloy 2A97 and the filler wire are given in table 1.

| Materials | Cu (wt.%) | Li (wt.%) | Zn (wt.%) | Mg (wt.%) | Mn (wt.%) | Zr (wt.%) | Si (wt.%) | Fe (wt.%) | V (wt.%) | Ti (wt.%) | Al (wt.%) |
|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 2A97      | 3.5-4.1   | 1.3-1.6   | 0.4-0.8   | 0.2-0.6   | 0.2-0.6   | 0.08-0.16 | -         | -         | -         | -         | Bal.      |
| ER2319    | 5.8-6.8   | -         | 0.1       | 0.2-0.4   | 0.2-0.4   | 0.1-0.2   | 0.2       | 0.3       | 0.05-0.15 | 0.1-0.2   | Bal.      |

2.2. Experimental setup
The dual-sided Laser beam welding (LBW) of the T-joints was performed using a 6-axis industrial robot which was connected to a YLS-5000 fiber laser through a delivering diameter of 200 µm. The focal lengths of the collimation lens and the focus lens were 200 mm and 250 mm respectively, yielding a focus diameter of 0.25 mm. During the experiments, the welding parameters used are given in table 2. No heat treatment was carried out on the welded T-joints post-welding.

Table 2. Welding parameters of the single-sided T-joint laser beam welding process.

| Welding parameters       | Values       |
|--------------------------|-------------|
| Laser power (P)          | 2000 W      |
| Welding speed (Vw)       | 2.4 m/min   |
| Wire feed rate (Vf)      | 4.5 m/min   |
| Incident beam position (d) | -0.2 mm    |
|                          | 0.2 mm      |
| Incident beam angle (β)  | 20°-45°     |
| Wire feed angle (θ)      | 20°         |
| Focal position (df)      | 0 mm        |
| Shielding gas flow rate  | 15 L/min    |

For retaining the position of the skin and the stringer during LBW, a mechanical clamping device was used. The filler wire was supplied by wire-filler machine. Argon gas was used as shielding gas during laser welding. The shielding gas was supplied from back of the molten pool. The used welding configurations is shown in Figure 1.
2.3. Microstructure analysis
The metallography and penetration of the welds under the different welding parameters was observed by optical microscopy. A scanning electron microscope (SEM) was used to study the fracture surface of the T-joints after tensile testing.

2.4. Mechanical testing
The mechanical properties of the joints were determined by the use of Vickers micro-hardness testing (HV 0.2). Therefore several indentations were made at all regions of the joint – fusion zone, heat affected zone and both base materials of skin and stringer. Tensile tests of welded T-joints were performed in order to assess the weld seam quality. Hoop-stress tests were performed on the welded T-joints by applying a load on the skin in perpendicular direction to the stringer. Here, the test represents the load condition in the skin of a pressurised fuselage. The results of welded joints are compared to the results of base material. The specimen geometry for the hoop tensile test is shown in Figure 2.

3. Results and discussion

3.1. Incident beam position
By the adjustment of the incident beam position it was possible to reduce the penetration into the skin to a minimum, to reduce the porosity and to improve the shape of the weld seam. The incident beam position is defined as the distance from the centre of laser beam on the stringer surface to the upper surface of the skin panel, and the optimal incident beam position is defined by the minimal achievable penetration into the skin with an adequate connection of the stringer to the skin. Thus the influence on the mechanical properties of the skin material is minimised. The required offset of the beam into the stringer strongly depends on the used welding parameters. Figure 3 shows the profiles of welded T-joints with different incident beam positions. Significant thermal deformation of the skin component was found to exit when the laser beam impinged onto the skin surface. This condition was incident beam position moved onto the stringer component, and the weld penetration was found to be reduced due to less laser energy being absorbed by the skin panel. The weld penetration with different incident
beam position is shown in Figure 4. The weld penetration into the skin is decreased with the values of the incident beam position rising.

Figure 5 shows the relationship between the incident beam position and the hoop tensile strength of T-joints. The hoop tensile strength of LBW T-joints of Al-Li alloy 2A97 is rising significantly while the weld penetration into the skin is decreased resulting from the increase of the incident beam position. The experimental results demonstrated that a maximum joint tensile strength for the hoop tensile test was realized when the incident beam position was 0.2 mm.

![Figure 3. Weld profiles with different incident beam positions (P=2000 W, Vw=2.4 m/min, Vf=4.5 m/min): (a) d=-0.2 mm, (b)d= 0 mm, and (c) d= 0.2 mm.](image)

![Figure 4. Weld penetrations into the skin of T-joints resulting from the different incident beam positions.](image)

![Figure 5. Relationship between the incident beam position and the hoop tensile strength of T-joints](image)

3.2. Incident beam angle

By the adjustment of the incident beam angle it was possible to reduce the penetration into the skin to a minimum, to reduce the porosity and to improve the hoop tensile strength of T-joints. The lower limit of the incident beam angle was defined by the geometry of the welding setup and excessive melting of the skin in front of weld seam, whereas the upper limit was defined by the occurrence of weld porosity due to the unfavourable temperature distribution. Therefore, the incident beam angles can only be varied between approximately 20° to 45°. Figure 6 shows the weld profiles with different incident beam angles. It can be seen that the weld penetration into the skin was increased significantly as the incident beam angle was increased (as shown in Figure 7).
Figure 8 shows the relationship between the incident beam angle and the hoop tensile strength of T-joints. The hoop tensile strength of LBW T-joints of Al-Li alloy 2A97 is increased firstly and then decreased while the weld penetration into the skin is increased resulting from the increase of the incident beam angles. The experimental results demonstrated that a maximum joint tensile strength for the hoop tensile test was realized when the incident beam angle was 35°.

Figure 6. Weld profiles with different incident beam angles (P = 2000 W, Vw = 2.4 m/min, Vf = 4.5 m/min): (a) β=20°, (b) β=35°, and (c) β=45°.

Figure 7. Weld penetrations into the skin of the T-joints resulting from the different incident beam angles.

Figure 8. Relationship between incident beam angle and hoop tensile strength of T-joints.

3.3. Microstructure
The optical micrograph, as shown in Figure 9, reveals the whole view of the T-joint. The distribution of microstructure of the cross-sectional weld of T-joints was observed. From the fusion line to the weld centre there is fine equiaxed grain, columnar grain and cellular dendrites respectively (as shown in Fig. 9(a), (b) and (c)). The heat affected zones (HAZ) between the skin (or stringer) and the fusion line is very narrow due to the low heat input and high welding speed during LBW.
Figure 9. Microstructure of T-joint: (P = 2000 W, Vw = 2.4 m/min, Vf = 4.5 m/min, d=0 mm, \( \beta = 35^\circ \)): (a) Microstructure near fusion line (stringer side), (b) Microstructure near fusion line (skin side), and (c) Microstructure at the centre of the weld.

3.4. Micro-hardness distribution

Micro-hardness tests were performed along the X direction and Y direction (micro-hardness measuring points locating at the red lines as shown in Figure 10) using a Vickers Micro-hardness tester with a load of 20 g and a dwell time of 12 s. The hardness profiles are plotted in Figure 10. The hardness at the centre of the weld is lower than that at HAZ and base metal (stringer or skin), because metal melting at the weld zone results in the loss of the strengthening phase in the base material.

Figure 10. Micro-hardness profiles along the X direction and Y direction of the weld (P = 2000 W, Vw = 2.4 m/min, Vf = 4.5 m/min, d=0 mm, \( \beta = 35^\circ \)).

3.5. Mechanical properties

Tensile properties of the T-joints revealed that the tensile strengths were significantly affected by the weld penetration into the skin of the T-joints. The hoop tensile strength of T-joints is decreased significantly with weld penetration increasing. The tensile strength of the hoop test of LBW T-joints of Al-Li 2A97 is up to 432 MPa when the weld penetration into the skin is about 0.5 mm.

Fractured sample from the hoop tensile test is shown in Figure 11. Since stress concentration exists at the weld toe on the skin panel side, fractures initiated in this area during tensile testing. During the hoop tensile test the fracture occurs along the fusion line up to around half thickness of the skin and then cracked through the base metal, as shown in Figure 11. SEM observations of the fracture surfaces from the tensile test specimens showed that the fracture morphology exhibited different characteristics in the hoop tensile test. The fracture surface appeared to be both intergranular and transgranular fracture at the weld toe and the fusion layer, lots of small dimples were found, and the slip characteristic was identified, as shown in Figures 12(a) and (b). It can be concluded that the fracture mechanism of the hoop tensile test specimen at the weld toe and fusion layer was brittle. While by observing the fracture surface of tested specimen near the unaffected skin panel base material, the surface presented a glide plane fracture appearance and the dimples had suffered from shear deformation, as shown in Figure 12(c), so the fracture mechanism of the tested specimen at the unaffected skin panel was ductile mode. Therefore, the fracture mechanism of the hoop tensile test is mixed fracture mode.
4. Conclusion
The incident beam position and incident beam angle strongly affected quality of the laser welded T-joints. The weld penetration was increased significantly as the incident beam position decreased or the incident beam angle increased. The optimal incident beam position was around 0.2 mm, and the optimal incident beam angle was 35°. The tensile strength of T-joints was up to 432 MPa when the weld penetration into the skin was about 0.5 mm. The significant softening occurred at the weld seam of T-joints due to the loss of strengthening phases in the weld. The fracture of the tensile specimens started at the weld toe, and then travelled along the fusion line, and finally travelled through the unaffected base material. SEM fractographs revealed that the fracture mechanism was mixed.

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