Laser welding of aluminium alloys for the aircraft industry

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Abstract. The results of laser welding of an Al-Mg-Mn and two Al-Mg-Li alloys with different lithium contents which used in the aircraft industry are presented in this paper. Microstructure, phase composition and mechanical properties of the welds were investigated. A fundamental difference in the processes of formation of structural-phase compositions in the weld metal of these alloys was found.

1. Introduction

Aluminum alloys of Al-Mg (e.g., Russian AMg5, AMg6) and Al-Cu-Mg (e.g., Russian D16 and 1163) systems are widely used for production of aerospace vehicles [1–3]. At the same time, progress in the aircraft industry is associated with using of contemporary high-strength aluminum alloys as structural material. To date, new aluminum-lithium alloys have been developed [4–6]. Alloying with lithium lowers metal density in comparison with traditional aluminum alloys. Examples are heat-treatable wrought alloys such as Al-Mg-Li-X (X = Zn, Mn, Zr, Sc), Al-Cu-Mg-Li, and Al-Cu-Li-X (X = Mg, Zn, Mn, Zr, Sc); Al-Cu-Li-X high-strength alloys as well as Al-Mg-Li-X average-strength ultra-light corrosion-resistant alloys.

Al-Mg-Li corrosion-resistant alloys (e.g., Russian 1420 and 1424) are the most promising candidates for replacing traditional Al-Mg alloys (e.g., Russian AMg6 and AMg5) in the aircraft industry. This is due to the fact that they have higher strength and fatigue characteristics. However, detailed studies of the properties of these alloys are necessary. Also, heat treatment (hardening, aging and annealing) and cold working procedures should be developed to improve structural-phase composition and mechanical properties. Different welding procedures (friction stir, gas tungsten arc, electron-beam, as well as laser-beam with and without filler wire) have been developed to replace riveted joints and, as a result, reduce weight of structures. However, welded joints of these Al-Li alloys made by fusion welding have low mechanical properties. It was shown in reviews on laser welding of aluminum alloys [7–9] that tensile strength of welded joints of Al-Mg-Li alloys is only about 60...85% of the base metal strength. The main reasons are burning-out of alloying elements with low melting point (magnesium, lithium, zinc, and manganese) as well as porosity and hot cracks in the weld metal. Optimization of welding parameters or using of filler wires was recommended by different authors to reduce the influence of these factors. The authors of papers [10, 11] presented microstructure and strength properties of the 2A97 alloy laser welds with and without filler wire. The weld strength was 84% of the base metal strength. In [12], the process of T-joint formation of 2060-T8/2099-T83 Al-Li alloys using laser welding with filler wire was studied; phase composition and mechanical characteristics of the welded joint were shown. In [13], laser welding of the 5A90
Al-Li alloy was investigated; microstructure and microhardness of the welds and the base metal were presented. However, it was not taken into account that these alloys are cold work- and precipitation-hardenable. Due to this fact their strength properties are determined by formation of hardening phases as a result of these treatments. Aluminum alloys of the Al-Mg-Li system are characterized by a complex phase composition which changes during heat treatment. This is due to the large number of alloying elements compared to traditional alloys. For example, Mg, Li, Zr, Sc, and Zn are present in the 1424 alloy. Alloying elements react chemically with aluminum. Therefore, in addition to the main strengthening δ-Al Li phase, double and triple intermetallic phases are formed in these alloys (for example, $S_i(Al_3MgLi)$ [14, 15]) which have a significant effect on strength and ductility of the metal.

The aim of the paper is to study regularity of changing in mechanical properties, microstructure and phase composition of AMg6, 1420, and 1424 aluminum alloys used in the aircraft industry during laser welding.

2. Materials and experimental procedure

The chemical compositions of the investigated aluminum alloys, which are a solid solution of α-Al with alloying elements, are given in Table 1. The AMg6 alloy also includes dispersed particles of AlMg2 (β-phase) and Al3Mn, which are the products of the solid solution decomposed during crystallization. The 1420 alloy contains hardening phases of AlLi (δ'-phase) and Al3MgLi (S1-phase) as well as dispersed particles of Al3(Zr) phase. The 1424 alloy distinguishes from 1420 a lower lithium concentration. It also contains hardening phases AlLi (δ'-phase) and Al3MgLi (S1-phase) but other dispersed particles (Al3Sc and Al3(Sc, Zr) phases).

Data on ultimate tensile strength ($\sigma_{UTS}$), yield strength ($\sigma_{0.2}$), elongation ($\delta$), and density $\rho$ of these alloys are shown in Table 2.

| Alloy | Al | Mg  | Mn  | Zn | Li | Zr | Sc | Ti | Fe |
|------|----|-----|-----|----|----|----|----|----|----|
| AMg6 | base | 5.8…6.2 | 0.5…0.8 | 0.2 | – | – | 0.02…0.10 | 0.4 |
| 1420 | base | 5.8…6.2 | 0.10…0.25 | 0.05 | 2.0…2.2 | 0.01 | – | – |
| 1424 | base | 4.7…5.2 | 0.05…0.25 | 0.4…0.8 | 1.61 | 0.09 | 0.07 | – |

| Alloy | $\rho$, g/cm³ | $\sigma_{UTS}$, MPa | $\sigma_{YS}$, MPa | $\delta$, % |
|------|--------------|-----------------|----------------|---------|
| AMg6 | 2.65 | 315…375 | 190 | 10.0 |
| 1420 | 2.50 | 440…450 | 280 | 18.5 |
| 1424 | 2.54 | 450…500 | 322 | 8.6 |

Butt joints were welded using a ‘Siberia’ automated laser technological facility (Figure 1, a) which includes a continuous wave CO₂ laser with a power of up to 8 kW [16]. It was developed at the Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch of Russian Academy of Sciences. Scheme of the laser welding process is shown in Figure 1, b. The laser beam was focused on the alloy surface using ZnSe lens with a focal distance of 254 mm. The beam diameter on the lens was equal to 25 mm. The diameter of the focused beam in its waist was evaluated as a sum of the diffraction diameter and diameter of the dissipation spot resulting from the spherical aberration. The calculated total diameter was 250 μm for the CO₂ laser.

An inert gas (helium) was used to protect the welded joint. The gas was fed through a nozzle tilted at an angle of 45° to the welded plates. The weld root was also protected with helium. The protective gas flow rate was 5 L/min.
Figure 1. Photograph of the ‘Siberia’ automated laser technological facility (a) and scheme of the laser welding process (b).

The oxide film was removed by means of chemical milling to a depth of 0.15…0.20 mm using 20% NaOH solution. The sample edges were scraped bright with a metallic scraper immediately before welding.

Firstly, the keyhole laser welding process was optimized in terms of speed, laser power, diameter and location of the focal spot, as well as shielding gas flow rate. Quality criteria were sound welds without any discontinuities such as pores, lack of fusion, undercuts and hot cracks. The optimal laser welding parameters are presented in Table 3.

| Alloy description | Thickness, mm | Laser power, kW | Welding speed, m/min | Focus position, mm |
|-------------------|---------------|-----------------|----------------------|-------------------|
| AMg6              | 1.5           | 2.6             | 4                    | -3                |
| 1420              | 1.4           | 2.7             | 4                    | -3                |
| 1424              | 1.6           | 2.9             | 4                    | -3                |

3. Results and discussion

Optical micrographs of the cross-sections of the weld metal, heat affected zone and the base metal are presented in Figure 2. The figure shows that all base alloys had a typical recrystallized structure. No dendritic structure was observed. Agglomerated particles in a wide range of sizes from tenths of a micrometer up to 10 µm were inside the metal matrix of a solid solution. The initial structure was transformed during laser welding and a typical granular structure was formed after crystallization. Dark agglomerates in the weld metal located mainly at boundaries of dendritic grains, making them very contrasting. The amount of dark agglomerates sharply increased in the welds of the studied aluminum alloys in comparison with the base metal. Their size was about 1…5 µm in most cases.

Images of the cross-sections of the etched welds and the base metal made using a scanning electron microscope (SEM) in the mode of backscattered electrons at different magnifications are presented in Figures 3 and 4. It follows from their comparison with Figure 2 that changes in microstructure of the welds and the base metal captured using electronic and optical microscopes coincide at the micron level. Uneven etching of the surface of the cross-sections indicates the uneven distribution of the main alloying elements in dendritic cells. Two types of inclusions can be distinguished on the basis of
obvious differences in morphology and color after etching: light and dark which are often combined into complex agglomerates with dimensions of 5…10 μm. The amount of the dark agglomerates in the welds is greater than in the base metal. The results of EDX analysis show an increase in Mg content in the dark agglomerates compared to the solid solution for the welds of the 1420 and 1424 alloys from 4.6 up to 5.6% and from 3.2 up to 5.5%, respectively; Mg diffused to the dendrite boundaries. Diffusion of Mg into the dark agglomerates did not occur in the AMg6 alloy.

**Figure 2.** Optical micrographs of the cross-sections of the weld metal, heat affected zone and the base metal.

**Figure 3.** SEM images of the cross-sections of the welds and the base metal.

**Figure 4.** SEM images of the cross-sections of the welds and the base metal.
In the AMg6 alloy, β-phase (Al₃Mg₂) particles with dimensions of 200 nm were observed at high magnification both in the base metal and in the weld. In the 1424 and 1420 alloys, two types of particles with sizes of 50 nm and 200 nm particles were found in the base metal. In the welds of these alloys, the dark particles with a size of 50 nm (apparently δ’ (Al₃Li)) were absent but the amount of the dark particles with a size of 200 nm (S₁ (Al₂MgLi)) increased.

Figure 5 shows diffraction patterns of the base metal which included intense reflections of the main α-Al phase as well as low-intensity reflections related to intermetallic phases. The AMg6 alloy had a number of reflections that could be Al₃Mg₂, Al₆Mn, and Al₅Mg₁₁Zn phases. Wide reflections of the Al₃Li phase were observed in the 1424 alloy. Perhaps, based on published data [15], they indicated presence of S₁ phase (Al₂MgLi). Intermetallics in the base metals were presented in very low concentrations. Intensity of the reflections of the intermetallic phases drops significantly in both alloys after exposure to laser radiation. This is due to their dissolution in the weld pool.

Figure 6 shows stress vs. strain dependences for the studied alloys and the welded joints. Tensile strength of the AMg6 alloy welds was almost 98% of the base metal strength, elongation was 86% of the base metal elongation. Tensile strength of the welds of the 1420 and 1424 alloys was 78% of the base metal strength; their elongation was about 13…28% of the base metal elongation.

It can be concluded based on the results of microstructural studies and XRD analysis that the strengthening phases were dissolved and Mg diffused from the solid solution to the dendrite boundaries in the 1420 and 1424 alloys due to the laser welding process. Only metastable S₁ (Al₂MgLi) was in the solid solution. This caused embrittlement of the welds. Magnesium diffusion was not observed in the AMg6 alloy weld metal, and the β-phase (Al₃Mg₂) was in the solid solution of both the base metal and the weld.

4. Conclusion

Comprehensive studies of laser welding of the AMg6, 1420, and 1424 aluminum alloys were performed. Microstructure, phase composition, and mechanical properties of the welded joints were investigated. The obtained results made it possible to reveal the fundamental features and differences in the crystallization processes of the studied aluminum alloys. Hardening phases formed in the 1420...
and 1424 alloys due to cold work and heat treatment were dissolved in the weld pool under the influence of laser radiation. This caused embrittlement of the welds.

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