Influence of structural and phase composition on mechanical characteristics of laser welded joints of aluminium-lithium alloys

A G Malikov and A M Orishich
Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, 630090, Novosibirsk, Russia
E-mail: smalik@ngs.ru, laser@itam.ncs.ru

Abstract. The paper presents the analysis of the structural and phase composition by the methods of electronic microscopy, X-ray diffraction analysis and synchrotron radiation of the laser welded joints for the Al-Li alloys of the systems Al-Cu-Li and Al-Mg-Li without and after the post thermal treatment. It is shown that during the welding, strengthening phases dilute in the solid solution of the welded joint, and, in the case of Al-Cu-Li alloys, they concentrate over the dendrite boundary. The optimal post heat treatment restores the structural phase composition and mechanical properties of the weld.

1. Introduction
Aluminum-lithium alloys feature low density and high strength as compared to ordinary aluminum alloys; they are promising materials for aircraft and space industries [1–2]. In order to replace riveting and reduce the weight of resulting structures, various technologies of welding of aluminum-lithium alloys are being developed intensively; among them, there are friction stir welding, laser welding, and electron-beam welding [3–5]. Laser welding has a number of advantages such as high process speed, small heating, flexibility, and capability of process automatization. However, the strength of the welded joints made by the laser welding of aluminum-lithium alloys is low and reaches 67% – 80% of the basic alloy strength [4, 6]. The main reason of the reducing strength of the welded Al-Li alloys lies in the changing structure- and phase composition. The high-rate heating, melting and subsequent crystallization result in essential changes in the structure and phase composition of the joint compared to the basic material. The melting process changes the micro-structure of the initial alloy and reduces the mechanical properties.

The purpose of this work is to study the structure and phase composition of welded joints of modern thermally-strengthened aluminum-lithium systems Al-Mg-Li and Al-Cu-Li as well as the impact of post-weld heat treatment (PWHT) on the mechanical properties and phase composition of the welded joint.

2. Experimental Technique
In this work, the alloy 1424 of the system Al-5.4Mg-1.61Li (CMg/CLi≈3.3) and the alloy V-1469 of the system Al-3.4Cu-0.66Mg-1.5Li (CCu/CMg≈5.1 and CCu/CLi=2.83) are used. The alloy 1424 is a promising material for the welded structure of fuselage in aircrafts of the MC family (Russia) and Airbus (EU). Its foreign analog is 5A90. The high-strength alloy V-1469 is applied as sheets, plates
and pressed profiles for fuselage shell and internal frame in modern aircrafts. Its foreign analog is 2195.

The base of these alloys is the $\alpha$(Al)-solid solution of alloying elements in aluminum with inclusion of different phases $\delta$‘(Al3Li), S1(Al2MgLi), T1(Al2CuLi), S’(Al2CuMg), T1(Al2CuLi), T2(Al6CuLi3), $\theta$‘(Al2Cu), plus coherent intermetallic phases Al3Sc and Al3Zr, both over grain boundaries and in the solid solution. These 1424 and V-1469 alloys are developed in FSBE “VIAM”, Russia and patented in Russia [7–9].

The aluminum-lithium alloys were welded in the automated laser technological complex “Sibir-1” developed in ITAM SB RAS [10]. In the experiments, we used a lens with the focal distance of 254 mm and falling radiation diameter of 30 mm; the minimal size of the focused radiation for the used laser with bpp (the beam parameter product) = 4.7 mm*mrad was $\approx$180 – 200 $\mu$m. The strength of the welded joints was measured in the servo-hydraulic machine Zwick/Roell Z100. Since the deformation is essentially nonuniform by length in the welded sample, the relative elongation of the working part was used for the comparison of the sample deformation; it was determined by the moving traverse motion.

After the welding, the cross sections of the welded joints were made by means of grinding and polishing. Micro- and nanostructures of the welded joint were studied with the scanning electronic microscope Zeiss EVO 50 XVP after etching using Keller solution. In order to achieve high resolutions, an ‘in-lens Duo’ detector was used with the ‘MERLIN Compact’ microscope. PWHT was carried out in the chamber furnace Carbolite. Quenching of the samples with the welded joint of alloy of the system Al-Mg-Li was carried out at 490 °C, (530 °C for the Al-Cu-Li alloy) within 30 minutes followed by cooling with water. The artificial ageing was optimized within the temperature range of 120 – 200 0°C for 4 – 42 hours. The phase analysis of the weld and alloy was investigated by two methods for reflection and transmission modes. The phase analysis of samples for transmission was performed with the synchrotron radiation (SR) in VEPP-3 (Institute of Nuclear Physics SB RAS) [11]. The beam size was 0.1x0.4 mm which enabled studying individually the transmission diffraction of both the alloy and welded joint. At the first stage, the laser welding was optimized in order to have a welded joint with no external defects, e.g., open porosity, undercuts, bad welding, cavities, discontinuities or cracks.

The welding was carried out in the keyhole mode; and the focal spot lied on the bottom sheet boundary. The optimal power of the laser beam was 2.7 kW for the alloy Al-Mg-Li and 3.5 kW for the alloy Al-Cu-Li; the welding rate was 4 m/min.

3. Results and Discussion

Figure 1 shows the characteristic change in the micro- and nanostructure of the welded joint melting zone (the system Al-Mg-Li) against the initial alloy, whereas Figure 2 shows the same for the Al-Cu-Li system.
Figure 1. SEM images of cross section of the joint (a) and alloy (b). System Al-Mg-Li. Magnification of 10 000× and 100 000×.

Figure 2. SEM images of cross section of the joint (a) and alloy (b). System Al-Cu-Li. Magnification of 10 000× and 100 000×.
The welded joint micro-structure differs fundamentally from the basic alloy structure. The melting process in the joint breaks the initial alloy microstructure.

Many dark agglomerates with the characteristic size of 0.5 – 1 μm form in the Al-Mg-Li system on the boundaries and in the volume of dendritic grains. There are no particles of 25 – 60 nm in the solid solution on the nano-level in contrast to the initial alloy. A few particles of 100 – 300 nm are observed. In the alloy in the solid solution, there are both fine (30 nm) and large (about 100 nm) dark particles.

The melting zone of the Al-Cu-Li system has a dendritic morphology, and white spots are evident (Fig. 2). They are located predominantly over the boundaries of the dendritic grains and form agglomerates of about 0.5 μm. It is seen at the nano-level that the agglomerates have a complex structure. Inside them, white particles of 20 – 30 nm stand out. These particles are absent in the solid solution of the welded joint, in contrast to the initial alloy. For the initial alloy, we observe only individual agglomerates up to 1 μm (see Fig. 2). However, with a large magnification, it is seen that in the solid solution of the alloy there are many small particles with a size of 20-30 nm. Table 1 presents the main mechanical characteristics of the tested thermally-strengthened samples with the welded joint and without it after stretching tests, where $\sigma_{UTS}$ is the ultimate tensile strength, $\sigma_{YS}$ is the yield strength, and $\delta$ is the elongation, the coefficient $k_i$ designates the ratio of welded joint / initial alloy, respectively.

Table 1. Mechanical characteristics of welded joints.

| System     | $\sigma_{UTS}$ (MPa) | $\sigma_{YS}$ (MPa) | $\delta$ (%) | $k_1$  | $k_2$  | $k_3$  |
|------------|----------------------|---------------------|--------------|--------|--------|--------|
| Al-Mg-Li   | 342                  | 270                 | 2.5          | 0.76   | 0.96   | 0.13   |
| Al-Cu-Li   | 306                  | 267                 | 0.7          | 0.55   | 0.52   | 0.09   |

The phase composition of the welded joint and alloy has been studied to understand the reason of such a dramatic strength reduction. Fig. 3 presents the diffractograms of the initial alloy and laser-welded joint obtained by the X-ray-phase analysis of reflection. The diffractograms are shifted vertically in respect to each other for better comparison.

**Figure 3.** X-ray patterns of the alloy (1) and welded joint (2) samples. Al-Mg-Li system.

On the alloy diffractogram, except for intensive reflexes of the Al phase, there are also additive reflexes. They may correspond to the $\delta'(Al_3Li)$ and $S_1(Al_2MgLi)$ phases. In the welded joint, only the metastable $S_1(Al_2MgLi)$ is fixed. The initial alloy and welded joint were also studied in advance by the X-ray diffraction method involving the synchrotronic radiation (SR) (see Fig.4). In contrast to Fig. 3,
the X-ray patterns obtained by the SR method show new peaks in the basic alloy. These peaks may belong to the $S_1(\text{Al}_2\text{MgLi})$, $(\text{Al}_3\text{Zr})$ and $(\text{Al}_3\text{Sc})$ phases. The strengthening $\delta'(\text{Al}_3\text{Li})$ phase is not registered in the welded joint, but the $S_1(\text{Al}_2\text{MgLi})$ phase is registered. Fig. 5, 6 present the X-ray patterns for the system Al-Cu-Li. There are many reflexes of copper-containing phases in the welded joint, which provides high reliability of the phase identification in the joint.

According to Fig. 5, intensive peaks, which may correspond to the strengthening $T_1(\text{Al}_2\text{CuLi})$ phase, are registered in the welded joint and alloy. The X-ray patterns obtained by the SR method show both the peaks of the strengthening $T_1(\text{Al}_2\text{CuLi})$ phase and new peaks in the basic alloy. These peaks may possibly belong to the $S'(\text{Al}_2\text{CuMg})$ phase. The data obtained with the synchrotronic radiation shows the promising future of the research of the welded joint phase composition by this method. According to the data obtained by SEM, X-ray and SR, the following may be suggested. During the solidification of the melt in the welded joint (the alloy of the system Al-Mg-Li), the triple $S_1(\text{Al}_2\text{MgLi})$ phase forms; its size is 100 – 300 nm, and it is located chaotically over the solid solution. The hardening phase $\delta'(\text{Al}_3\text{Li})$ is absent in the weld. For the alloy of the system Al-Cu-Li, the copper-containing $T_1(\text{Al}_2\text{CuLi})$, $S'(\text{Al}_2\text{CuMg})$ phases form on the dendrite boundary; they are absent in the solid solution. Copper diffusion from the solid solution and localization of strengthening copper-containing phases on the dendritic grain boundaries lead to the reduction of the welded joint strength.

To reach the maximal strength of the thermally strengthened alloys, it is necessary to reach a certain intermediate nonequilibrium structure by means of scheduled heating due to admixture phase solution; this structure corresponds to the initial stages of disintegration of the oversaturated solid solution during which strengthening phases form in the solution. This structure is achieved owning to the post thermal processing as quenching followed by artificial ageing [12, 13]. The maximal $\sigma_{UTS}\approx 510$ MPa is reached in the sample with the welded joint of the system Al-Mg-Li within the temperature range of 170 – 180 °C for 6 – 8 hours. In the case of sample with the welded joint of the system Al-Cu-Li, $\sigma_{UTS}\approx 500$ MPa the temperatures range of 190 – 200 °C for 32 – 40 hours. The optimization of the regimes of thermal processing of the laser-welded joints allowed obtaining the mechanical characteristics approaching or equal to the ones of the initial alloy at feeding conditions in Table 2.

| System      | $\sigma_{UTS}$ (MPa) | $\sigma_{YS}$ (MPa) | $\delta$ (%) | $k_1$  | $k_2$  | $k_3$  |
|-------------|----------------------|--------------------|--------------|--------|--------|--------|
| Al-Mg-Li    | 500                  | 360                | 6.6          | 1.00   | 1.12   | 0.92   |
| Al-Cu-Li    | 526                  | 476                | 3.5          | 0.94   | 0.93   | 0.58   |

Fig. 7 shows the characteristic variation of the melting zone nanostructure (the welded joint of the system Al-Mg-Li and Al-Cu-Li) in the optimal quenching and artificial ageing regimes.
Figure 7. SEM of nanostructure of cross section of the welded joint after heat treatment. 

a) welded joint Al-Mg-Li, b) welded joint Al-Cu-Li.

Post-weld heat treatment results in the essential change of the welded joint nanostructure. The nanostructure of welded joint approaches the nanostructure of the base alloy (Fig. 1, 2). Similar morphology is formed in the joint of dark Al-Mg-Li particles and light ones for the system Al-Cu-Li in the solid solution of the welded joint. Analysis of the precise phase composition requires further XRF and SR investigations.

Conclusions
The technology of the laser welding has been applied for the aluminum-lithium alloys; it is based on the optimization of the laser welding and post thermal processing. It is demonstrated that the structure-phase composition of the welded joint differs from the initial alloy. For the system Al-Mg-Li, the strengthening δ′(Al3Li) phase dilutes in the welded joint. For the alloy of the system Al-Cu-Li, copper-containing T1(Al2CuLi), S′(Al2CuMg) phases form on the dendrite boundaries. The pioneering mechanical characteristics of the aluminum-lithium alloys comparable with the ones of the alloy in the feeding condition have been reached for the welded joints made by the laser welding and optimal post processing.

Acknowledgments
The work is supported by the grant of the Ministry of Education and Science of the Russian Federation No. 2020-1902-01-039. The authors are grateful to A.I. Ancharov. The work was done at the shared research center SSTRC on the basis of the Novosibirsk FEL/VEPP-4 - VEPP-2000 complex at BINP SB RAS.

Reference
[1] Rioja R J and Liu J 2012 Metall. Mater. Trans. A Phys. Metall. Mater. Sci. 43 3325–37
[2] Abd El-Aty A, Xu Y, Guo X, Zhang S-H, Ma Y and Chen D 2018 J. Adv. Res. 10 49–67
[3] Chen G, Yin Q, Zhang G and Zhang B 2020 J. Manuf. Process. 50 216–23
[4] Kashaev N, Ventzke V and Çam G 2018 J. Manuf. Process. 36 571–600
[5] Çam G and İpekoğlu G 2017 Int. J. Adv. Manuf. Technol. 91 1851–66
[6] Xiao R and Zhang X 2014 J. Manuf. Process. 16 166–75
[7] Khokhlatova L B, Kolobnev N I, Oglodkov M S 2012 Metallurgist 56 336–41
[8] Lukina E A, Alekseev A A, Khokhlatova L B and Oglodkov M S 2014 Met. Sci. Heat Treat. 55 466–71
[9] Betsofen S Y, Antipov V V. and Knyazev M I Russ. Metall. 2016 326–41
[10] Malikov A, Orishich A, Golyshiev A and Karpov E 2019 J. Manuf. Process. 41 101–10
[11] Ancharov A I 2017 Russ. Phys. J. 60 543–9
[12] Malikov A, Bulina N, Sharafutdinov M and Orishich A 2019 Int. J. Adv. Manuf. Technol. 104 4313–24
[13] Annin B D, Fomin V M, Karpov E V., Malikov A G and Orishich A M 2017 J. Appl. Mech. Tech. Phys. 58 939–46