Influence of thermal processing on the structural and phase content of high-strength laser welded joints of the aluminum alloy system Al-Mg-Li

A G Malikov, 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 deals with the analysis of the structural and phase content of the laser welded joints and basic alloy 1424 of the system Al-Mg-Li by electronic microscopy and X-ray analysis. The total comparative investigation has been carried out to evaluate the influence of the thermal processing such as quenching and artificial ageing on the mechanical properties and structure of welded joints and basic alloy. The investigation shows that the welded joint structure is dendritic. In the welded joint, the two-phase state of the solid solution is observed after the re-melting (α-Al+S1(Al2MgLi)), the strengthening phase δ′(Al3Li) is diluted. The thermal processing (quenching and artificial ageing) of the welded joint (alloy 1424) results in the increased tensile strength of up to 0.95 of the basic alloy strength.

1. Introduction
There are specific requirements concerning minimal weight, high strength, long life and cost-effectiveness of welded constructions that are put forward for the materials that are used in the welded constructions of aircraft and aerospace vehicles. The use of Al-Li constructional alloys with low density and improved strength properties is of high priority for modern air vehicles improvement. However, fluid welding of the alloys that are rather far-reaching for modern air vehicles implies specific difficulties. As a result, the joint of the alloys that contain lithium obtained with the help of fluid welding demonstrates poor mechanical behavior.

The solution of this issue may let us get rid of a very laborious and ineffective technology of riveted joint of details that requires millions of rivets, which is used now because of high strength and fatigue life of such joints that have utmost importance for the aviation.

As of now, new high strength heat hardenable wrought alloys of different systems have been developed, for example: Al-Mg-Li, Al-Cu-Mg-Li, Al-Cu-Li with reduced density [1-3]. High rate of static strength of these systems is due to the unique phase composition that is formed during the heat treatment [2, 4-7].

The prospects of friction stir welding, argon arc welding, and laser beam welding are examined [8-14]. At the moment, the welded joint strength of Al – Li system alloy with various addition agents is k=0.7-0.85 of the strength of base material [8, 13-14] without additional treatment of weld.

The main reason why welded joint strength is lowering is commonly believed to be burning of volatile addition agents, such as Mg, Li, Zn, Mn, occurrence of gas pockets and autocracks in the weld
In order to minimize such negative processes, according to various sources, either welding condition optimization or filler is used. At the same time, it seems to be defined that in order to improve weld strength of modern Al alloys of Al-Cu-Li and Al-Mg-Li systems, it’s necessary to do additional mechanical and heat weld treatment. Thus, in the articles [14, 15] the influence of various welded joint deformation types on joint strength has been examined. It is shown that for the Al alloy 1424 (system Al-Mg-Li) welded joint strength after the deformation will increase by 20% [14]. For Al-Cu-Li system, the improvement of mechanical characteristics can be acquired by using the complex method that includes laser beam welding in optimal conditions and heat treatment of the welded sample [15]. It is shown that various addition agents can substantially change the structure of the weld. These conditions stimulated the authors to conduct a research of laser welding and heat treatment influence on the microstructure of the welds of Al-Mg-Li systems.

In this article we study heat treatment on the microstructure and strength of the alloys’ welds 1424-(Al-Mg-Li system) developed at FSUE VIAM Russia [3,6] and protected by Russian patents No. 2133295.

2. Experimental Technique
Laser welding was performed on the Sibir-1 automated laser technological complex, which includes a continuous-wave CO₂ laser with a power of up to 8 kW developed at the Kristianovitch Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Russian Academy of Sciences. The laser beam was focused on the alloy surface with the help of a ZnSe lens with a focal distance of 254 mm. An inert gas (helium) was used for welded joint protection. The oxide film was removed by means of chemical milling to a depth of 0.15÷0.20 mm. Directly before welding, the sample edges were scraped bright with a metallic scraper. Table 1 presents the chemical composition of the alloy 1424 [3].

| Chemical composition of alloy (wt. %). |
|---------------------------------------|
| Al | Mg | Li | Zn | Zr | Sc |
|----|----|----|----|----|----|
| base | 5.4 | 1.61 | 0.7 | 0.09 | 0.07 |

The spectral analysis of the welded joint and base alloy was performed on a LEO 1430 VPI scanning electron microscope equipped with an IPX OXFORD energy detector. Heat treatment was performed in a Carbolite batch furnace equipped with a temperature controller. The samples were cut on automatic and polishing machines for sample preparation (Presi).

The strength of the welded joints was measured at the static extension on the electro-mechanical test machine Zwick/Roell Z100. The test samples with the herringbone structure across the joint were made in accordance with the GOST ISO 4136-2009.

XRD patterns were recorded by a D8 Advance powder diffractometer with Θ-Θ geometry equipped with a one-dimensional Lynx-Eye detector and Kβ filter using Cu Kα radiation in the interval of 5° < 2θ< 90° with a step size of Δ2 θ = 0.0195° and a counting time of 35.4 s per step. The XRD structure analysis was performed by the Rietveld method using Topas 4.2 software (Bruker AXS, Germany).

Laser beam welding joints samples were obtained in the following welding mode: laser power of 3 kW, welding speed 4 of m/min, focus forced into the material -3mm.

After welding, the samples underwent heat treatment. For the alloys 1424, (Al-Mg-Li system) the following heat treatment modes were chosen: quenching with heating up to 450°C for 30 min and further air cooling, the heating rate of 8°C/min; the samples were subjected to artificial ageing at 120 °C for 12 h. The rate of heating up to 120 °C was 5°C/min.
3. Results and Discussion

Figure 1 presents the SEM images demonstrating the influence of heat treatment: quenching and quenching with artificial ageing on the microstructure in the base alloys and welded joint.

![Alloy](image1)

![Welded joint](image2)

**Figure 1.** SEM images of the weld microstructure cross section and base alloy of the Al-Mg-Li system (magnification 7000x) a) No heat treatment b) Quenching c) Quenching+artificial ageing

In the process of welding, in the weld pool of an alloy complete destruction of the original material structure has occurred, and during crystallization a typical grained structure has been formed. In the shots made with SEM, aside for dark agglomerates (Figure 2), there are occasional light precipitates, the size of 3 – 10 \( \mu m \), which exist both in the initial alloy and in the weld.

![Figure 2](image3)

**Figure 2.** SEM images of light precipitate. a) base alloy b) welded joint

These precipitates contain much zirconium (13.27 –19.78 % wt. ) and scandium (3.48 – 4.72 % wt). It is fair to assume that the phase Al\(_3\)(Sc, Zr) forms in these primary precipitations.
Figure 3 presents the preliminary results of the comparative XRD patterns of the phase composition for the alloy and welded joint.

![Graph showing XRD patterns](image)

**Figure 3.** XRD patterns of the base alloy and welded joint. 1) alloy 1424 2) welded joint

As is evident from Figure 3, the phase composition of the welded joint changes. Solidifying phases δ’ (Al3Li) for the system Al-Mg-Li disappear, the reflexes of the S1 (Al2MgLi) occur.

Disintegration of the supersaturated solid solution for aluminum alloys of the system Al-Mg-Li follows this way:
\[
\alpha\text{ (supersaturated solid solution) } \rightarrow \delta'\text{ (Al}_3\text{Li) } \rightarrow \text{S}_1\text{ (Al}_2\text{MgLi)}
\]

It is assumed on the investigation results base that during laser welding of the alloys of the system Al-Mg-Li, the strengthening phase δ’(Al3Li) is diluted in the solid solution, and then the metastable phase S1(Al2MgLi) is formed over the boundaries of the dendrite grain. S1(Al2MgLi) is seen as dark and light grey particles.

After quenching, S1(Al2MgLi) released in the basic alloy (see Figure 1 (b)). For the welded joint after the quenching, partial dilution of S1(Al2MgLi) occurred. Quenching + artificial ageing lead also to insignificant dilution of S1(Al2MgLi).

Table 2 contains the data about the ultimate tensile strength σUTS, ultimate yield strength σYS, and relative elongation δ of the base alloy, welded joint and heat-treated weld and alloy 1424 systems Al-Mg-Li. Also, in the tables there are indexes k, that reflect the changes of the given values in relation to the base alloy depending on various modes. For each mode at least 3 samples were examined.

| Mode                              | σUTS, MPa | k₁  | σYS, MPa | k₂  | δ, %     | k₃  |
|-----------------------------------|-----------|-----|-----------|-----|----------|-----|
| Base alloy                        | 463       | –   | 322       | –   | 8,6      | –   |
| Welded joint                      | 376       | 0,81| 281       | 0,87| 2,4      | 0,28|
| Welded joint after quenching      | 380       | 0,82| 195       | 0,61| 19,2     | 2,23|
| Welded joint after quenching, and artificial aging | 438 | 0,95 | 267 | 0,83 | 13,3 | 1,55 |

In Al-Mg-Li alloys there are two main phases: non-equilibrium phase δ’(Al3Li) which is a strengthening phase, and equilibrium S1 phase (Al2MgLi); structural changes of these phases depending on the heat treatment type are being examined [3, 6, 7]. Thus, in the paper [7] it is shown that the range
of temperature changing for $S_1$ phase ($\text{Al}_3\text{MgLi}$) is 200–450°C (quenching), and for phase $\delta'\text{Li}$ the temperature range is 100–175°C (artificial ageing). In the article [7] it is shown that phase $S_1(\text{Al}_3\text{MgLi})$ plays unimportant role for the Al-Mg-Li system alloy strength, the authors claim that to achieve the maximum of strength properties it is necessary to optimize the artificial ageing modes, and change the chemical compound of the alloy. Also, the authors of [3, 7] write that it is necessary to control the growth of phase $S_1(\text{Al}_3\text{MgLi})$ depending on the temperature and treatment time.

Using the results of this paper and [3, 4, 7] as a base in order to have the strength of the welded joint on equal to the basic alloy strength ($k_1 = 1.00$), one should dilute the phase $S_1(\text{Al}_3\text{MgLi})$ in the welded joint due to the optimization of the modes (temperature) of quenching. And then, the strengthening phase $\delta'\text{Li}$ is separated due the optimization of the artificial ageing time and temperature.

4. Conclusion

Concentration of the strengthening phase $\delta'\text{Li}$ reduces in the welded joint, which results in the low mechanical characteristics. The full thermal mechanical processing (quenching, artificial ageing) of the welded joint of the aluminum alloy 1424 (system AL-Mg-Li) results in the tensile strength increase of up to 0.95 of the basic alloy strength. To have the welded joint strength equal to the basic alloy strength 100%, it is needed to optimize the quenching temperature and dilute the phase $S_1(\text{Al}_3\text{MgLi})$ in the welded joint, as well as the artificial ageing time and temperature, which permit to separate the strengthening phase $\delta'\text{Li}$.

Acknowledgments

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