Investigation of the phase composition and mechanical characteristics of laser welded joints of aluminum-lithium alloys

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Abstract. A study of laser welding of modern aluminum-lithium alloys has been carried out. Optimization of post heat treatment of laser welded joints has been carried out. The change in the structural-phase composition of welded joints was investigated. The strength of welded joints after heat treatment was equal to the strength of the base alloy.

1. Introduction

Increasing the weight efficiency is traditionally considered one of the main tasks of modern aircraft and rocketry. One of the possible solutions to this problem is the use of aluminum-lithium alloys in welded structures.

Modern high-strength thermally hardened aluminum-lithium alloys are considered one of the most promising for use in the aerospace industry, due to their high mechanical characteristics: strength, stiffness, ductility, machinability and corrosion resistance. This allows them to compete with traditional aluminum alloys and polymer composite materials. High mechanical properties of these alloys are provided due to special thermomechanical treatment, which results in the formation of strengthening phases δ′(Al₃Li), T₁(Al₂CuLi), T₂(Al₅CuLi₃), θ″, θ′ (Al₃Cu), θ (Al₂Cu), R (Al₅CuLi₃), T₀(Al₃CuLi). Depending on the ratio of the concentrations of the main alloying elements Cu, Mg Li, the role of these phases involved in the hardening mechanism is different.

When creating structures and products from these alloys in aircraft construction, the technology of riveted joints is usually used, the main disadvantages of which are high labor intensity, negative impact on the environment and humans. The use of riveted joints is largely due to the fact that the ultimate strength of various types of welded joints of these alloys is 0.6–0.85 of the strength of the base material. A decrease in the mechanical properties of welded joints is associated with a sharp change in the structural-phase composition of the weld in comparison with the original alloy. The aim of the work is to obtain high-strength laser welded joints of aluminum-lithium alloys with different concentrations of alloying elements by optimizing the operating modes of laser during welding and post heat treatment of the obtained samples.
2. Experimental Technique

In this work, the alloy 1420 of the Al-Mg-Li-X system \((X = \text{Zr, Zn, Sc})\) was used, which is an industrial alloy for aviation purposes (welded sealed compartments, window frames, hatches, cockpit components, etc.). This alloy was used in the construction of Yak-36, Yak-38, MiG-29M, Su-27, Yak-42, Tu-204 aircraft. The high-strength alloy V-1469 was developed on the basis of the Al-Cu-Li-X system \((X = \text{Zn, Zr, Sc, Mg})\) and has found its application in the fuselages of modern aircrafts. These alloys were developed at FSUE "VIAM" and now are protected by RF patents. The basis of these alloys is an \(\alpha\)-solid solution of alloying elements in aluminum \((\alpha-\text{Al})\), with the inclusion of various phases \(\delta'(\text{Al}_2\text{Li}), S1 (\text{Al}_2\text{MgLi}), T_1(\text{Al}_2\text{CuLi}), S'(\text{Al}_2\text{CuMg}), T_1(\text{Al}_2\text{CuLi}), T_2(\text{Al}_2\text{CuLi}), \theta' (\text{Al}_2\text{Cu}),\) as well as coherent phases of intermetallic compounds Al3Sc and Al3Zr both along grain boundaries and in solid solution [1–4]. Alloys in the form of sheets with a thickness of 1.4 - 2 mm were purchased KUMZ (Russia).

Laser welding of aluminum-lithium alloys was carried out on the automated laser technological complex "Siberia-1", developed at the ITAM SB RAS [5,6]. Laser radiation was focused on the alloy surface using a ZnSe lens with a focal length of 254 mm. An inert gas (helium) was used as shield gas. The oxide film was removed by chemical milling to a thickness of 0.15 – 0.20 mm. Immediately before welding, the edges of the samples were brushed off with a metal scraper. The strength of the welded joints was measured on a Zwick / Roell Z100 servo-hydraulic machine. Since the deformation in the welded specimen is substantially inhomogeneous along the length, to compare the deformation of the specimen, the relative elongation of the working part, which was determined by the movement of the movable crosshead, was used.

After the welding process, thin sections of welded joints were prepared by grinding followed by polishing. Macro- and microstructure of welded seams were investigated on an Olympus LEXT OLS3000 optical microscope after etching in Keller's reagent. The determination of the chemical composition of the weld and the base alloy was carried out using a scanning electron microscope "EVO MA 15" (Carl Zeiss,). Heat treatment was carried out in a Carbolite chamber furnace. The phase composition of the obtained samples was studied by powder X-ray diffraction and synchrotron radiation at VEPP3 (BINP SB RAS) [7]. 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.

3. Results and Discussion

At the initial stage, the laser welding process was optimized in order to obtain welded joints without external defects in the form of open porosity, undercuts, non-penetrations, cavities, discontinuities, cracks.

The criterion for the quality of the internal microstructure and morphology of the laser welded seam of butt joints was the minimum porosity, as well as equality of the width of the upper and root parts and obtaining an X-shaped butt weld with two curved bevels of two edges [8]. An X-shaped weld can have advantages in mechanical properties due to a more symmetrical centerline weld [9].

The range of variation of the laser power \(W\) was 2-3.5 kW, the position of the focal spot of the laser radiation relative to the surface of the workpiece was -3 to +3 mm, the welding speed \(V\) was 2-5 m / min (33.3-100 mm / s), the consumption gas in the nozzle was 3-15 l / min. Laser was focused using a ZnSe lens with a focal length \(f = 254\) mm. The diameter of the laser radiation incident on the lens is \(D = 30\) mm. The focused beam diameter at the focus is \(\approx 168\) \(\mu\) for this type of CO2 laser.

Figures 1 and 2 show typical optical photographs of the macrostructure of the weld cross-section when optimizing the welding speed at constant laser power for alloy 1420 of the Al-5.2Mg-2.1Li system and V-1469 of the Al-3.9Cu-0.3Mg-1.2 system. Li. A laser power was 2.7 and 3.3 kW for alloy 1420 and V-1469, respectively, focus deepening was -3 mm.
Figure 1. Photos of the microstructure of the cross-section of the weld at different welding speeds of 1420 alloy of Al-5.2Mg-2.1Li system.
a) 4 m/min, b) 3 m/min, в) 2 m/min.

Figure 2. Photos of the microstructure of the cross-section of the weld at different welding speeds of V-1469 alloy of Al-3.9Cu-0.3Mg-1.2Li system
a) 5 m/min, b) 4 m/min, в) 2 m/min.

Figures 3 and 4 show the microstructure of the weld at different laser power for 1420 and B-1469 alloys, at a welding speed of 4 m/ min and a deepening of the focus equaled to - 3 mm.

Figure 3. Photo of the microstructure of the cross-section of the weld depending on the power of the laser radiation. 1420 alloy.
a) 3 kW, b) 2.7 kW, c) 2.4 kW, d) 2 kW.
Figure 4. Photo of the microstructure of the cross-section of the weld depending on the power of the laser radiation. V-1469 alloy.

a) 3.3 kW, b) 3 kW, c) 2.7 kW, d) 2.5 kW.

Figure 5 shows the dependence of the change in the coefficient $k$ of the ratio of the values of the width of the welded seam of the upper and root parts on the welding speed $V$ and of the laser power $W$ for the 1420 and V-1469 alloys.

Figure 5. Dependence of coefficient $k$ on welding speed $V$ (a) and laser power $W$ (b)

1-alloy 1420, 2-alloy V-1469

Coefficient $k$ decreases with decreasing welding speed, while (see Fig. 3.1) X-shaped form of weld seam disappears for alloy 1420. For alloy V-1469 coefficient $k$ increases with decreasing welding speed. This indicates different processes of crystallization of the melt of aluminum alloys, depending on the main alloying element - Mg or Cu. Analyzing Figures 3.1.1 and 3.1.2, a welding speed of 4 m/min can be considered optimal for the alloys under study.

The minimum value of the coefficient $k$ for the weld of alloy 1420 is achieved at two values of the laser power, 2.7 and 2 kW. At a power of 2 kW, there is no X-shape of the weld, and undercuts and sagging of the weld are also observed. For a welded seam of alloy B-1469, the coefficient $k$ decreases with increasing laser power. The X-shape of the welded seam is achieved at a power of 3.3 kW.

At a welding speed of 4 m/min and a laser power of 2.7 kW for alloy 1420 and 3.3 kW for alloy V-1469, optimization was carried out according to the position of the laser radiation focus relative to the upper boundary of the sheet.

Figures 6 and 7 for alloy 1420 and V-1469, respectively, show the microstructure of the weld at different focal positions $\Delta f$ relative to the upper border of the sheet. According to Figures 6 and 7, when the focus is on the surface, the porosity of the welded joint is maximum; when the focus is deepened into the material, the porosity decreases. The optimal focus position, when the porosity is minimal, was 3 mm from the upper border of the sheet being welded.
Figure 6. Optical microstructure of the weld cross-section at different focal positions.
a) Δf - 3 mm, b) Δf - 1.5 mm, c) Δf 0 mm. Alloy 1420.

Figure 7. Optical microstructure of the weld cross-section at different focal positions.
a) Δf - 3 mm, b) Δf 0 mm, c) Δf +3 mm. Alloy V-1469.

Pore formation mechanisms are rather complicated. The hydrodynamics of the melt flow on the walls of the steam-gas channel has a dominant effect on the defects of the welded seam [10]. At very low welding speeds, the gas-vapor channel is unstable because the laser beam irradiates the front wall of the channel, which causes the molten metal to move to the bottom of the weld. When the laser beam moves, a collapse process occurs, at the same time, a high welding speed leads to a melt flow along the side walls of the vapor-gas channel, but at high welding speeds, no penetration may occur. It is needed to keep the speed balance while welding. The influence of the focus position in the mode of dagger penetration and thermal conductivity during laser welding of aluminum alloys is theoretically considered in detail in [11]. The profile of the weld in the dagger penetration mode was calculated based on the energy balance on the wall of the steam-gas channel, where the temperature was taken to be equal to the boiling point of the alloy. The three-dimensional temperature field of the weld was calculated taking into account the thermal conductivity. As a result, it was shown that deepening the focus leads to an increase in the penetration and, thereby, to a decrease in the porosity of the weld. It can be assumed that in our case, the optimal balance of power, speed and focus position leads to a decrease in the porosity of the weld.

Optimization in terms of shielding gas consumption showed that an unoxidized weld seam is obtained with a helium shielding gas flow rate of more than 4 l/min. Welding was carried out at a Helium flow rate of 5 l/min.

Based on the research and analysis performed, Table 1 presents the optimal modes for obtaining laser welded joints without external defects in the form of undercuts, discontinuities, cracks, pores, and sagging of the weld.

Table 1 also presents estimates of the energy conditions for obtaining a high-quality weld under optimal welding conditions for a given sheet thickness: P is the heat input equal to the ratio W / V, E is the energy per unit of volume of the molten material equal to W/Vth, where t is the thickness of the alloy, h is average width of the weld.
### Table 1. Optimal energy conditions for laser welding.

| Alloy  | \( t, \) mm | \( W, \) kW | \( V, \) m/min | \( \Delta f, \) mm | \( P, \) J/mm | \( E, \) J/mm² |
|--------|-------------|-------------|--------------|---------------|-------------|-------------|
| 1420   | 1.4         | 2.7         | 4            | -3            | 39.6        | 40.5        |
| V-1469 | 2           | 3.3         | 4            | -3            | 25          | 49.5        |

It can be seen from Table 1, for copper-containing alloys, the energy per unit volume of the weld is higher than for alloys containing magnesium, while the heat input is, on the contrary, higher.

As a result, the parameters of the laser welding process of the studied aluminum alloys were optimized: welding speed, radiation power, diameter, depth and location of the focal spot, as well as the consumption of a protective neutral gas in order to obtain welded joints without external defects.

Table 2 shows the main mechanical characteristics of samples with a welded seam of the investigated heat-strengthened alloys after tensile tests, where \( \sigma_{UTS} \) is the ultimate strength, \( \sigma_{YS} \) is the yield strength, \( \delta \) of plasticity limit.

### Table 2. Mechanical characteristics of welded joints.

| Alloy  | \( \sigma_{UTS}, \) (MPa) | \( \sigma_{YS}, \) (MPa) | \( \delta, \) (%) |
|--------|----------------------------|--------------------------|------------------|
| 1420   | 342                        | 270                      | 2.5              |
| V-1469 | 310                        | 295                      | 0.7              |

The decrease in strength is caused by the peculiarities of the structure of the material. Fig. 8 shows the diffraction patterns of the initial alloy 1420, V-1469 and the laser weld obtained by X-ray phase analysis in transmission using synchrotron radiation. The diffractograms are vertically displaced relative to each other for ease of comparison.

![Diffraction patterns](image)

**Figure.** 8. Reflection and transmission X-ray diffraction patterns

a) alloy 1420, b) alloy V-1469 1) alloy 2) weld

In the diffraction pattern of alloy 1420, in addition to intense reflections of the Al phase, additional reflections are also presented. These reflexes can correspond to the phases \( \delta'(Al_3Li); S_1(Al_2MgLi) \). In the welded joint only the metastable phase \( S_1(Al_2MgLi) \) was recorded.

In the initial V-1469 alloy, the most intense reflections of impurity phases correspond to the \( T_1 \) and \( \theta(Al_2Cu) \) phases. Strong reflections of the \( T_1 \) phase \( (Al_2CuLi) \) and the \( \theta(Al_2Cu) \) phase are observed in the welded joint.
In the process of solidification of the melt in the weld of alloy 1420 (Al-Mg-Li system), a triple phase \( S_1(Al_2MgLi) \) was formed, randomly located in the solid solution; there is no strengthening phase \( \delta'(Al_3Li) \) in the weld (see Fig. 9 a). For the V-1469 alloy (Al-Cu-Li system), the Cu solid solution is depleted and concentrated at the dendrite boundary with the formation of copper-containing phases \( T_1(Al_2CuLi), \theta(Al_2Cu) \). (see Fig.9b).

![Figure 9](image)

**Figure 9.** Nano structure of the weld. a) alloy 1424, b) alloy V-1469

To achieve the maximum strength of thermally hardened alloys, it is necessary to obtain some intermediate nonequilibrium structure, which corresponds to the initial stages of the decomposition of a supersaturated solid solution, during which strengthening phases are formed in the solid solution, using regulated heating due to the dissolution of impurity phases [12].

For welded joints of alloy 1420, the heat treatment modes were: quenching at a temperature of 490 °C and a time of 30 min, followed by artificial aging at a temperature of 170 °C and the duration of 16 hours. For laser welded joints of alloy V-1469, the heat treatment modes were quenching at a temperature of 560 °C with a holding time of 30 min, followed by artificial aging at a temperature of 180 °C and the duration of 32 hours.

The hardening of alloy 1420 of the Al-Mg-Li system made it possible to significantly dissolve the metastable \( S_1(Al_2MgLi) \); the hardening phase \( \delta'(Al_3Li) \) is nearly absent in it. Alloying components in intermetallic phases (in particular, in the triple phase \( S_1(Al_2MgLi) \)) completely or partially dissolved in aluminum, and an extremely nonequilibrium state was formed - a supersaturated solid solution of alloying elements Mg and Li in aluminum. The hardening of samples of the Al-Cu-Li systems increases the concentration of copper in the solid solution, which is determined by the dissolution of copper-containing phases at the boundaries of dendritic grains.

Artificial aging of alloy samples of the Al-Mg-Li system makes it possible to ensure the precipitation of the main strengthening intermetallic phase \( \delta'(Al_3Li) \) in the weld, which is confirmed by the XRD analysis. For alloys of the Al-Cu-Li system, copper-containing phases are formed in a solid solution. Optimization of artificial aging for redistribution of strength depending on time and

The results of optimization of the modes of heat treatment of laser welded joints made it possible to obtain mechanical characteristics close to or equal to the original alloy.

**Table 3.** Mechanical characteristics of welded joints after heat treatment.

| Alloy  | \( \sigma_{UTS} \) (MPa) | \( \sigma_{YS} \) (MPa) | \( \delta, (%) \) |
|--------|------------------------|------------------------|------------------|
| 1420   | 444                    | 275                    | 6,0              |
| V-1469 | 530                    | 485                    | 3,9              |
4. Conclusions

The technology of laser welding of aluminum-lithium alloys has been developed, based on the optimization of the laser welding process and post heat treatment.

For laser welded joints and optimal post-processing, the mechanical characteristics of the aluminum-lithium alloys are comparable to those of the alloys as delivered.

It was found that for alloy 1420, the strengthening phase δ′(Al3Li) dissolves in the solid solution of the weld. For alloy V-1469, copper-containing phases T1(Al2CuLi), θ(Al2Cu) are formed at the dendrite boundary.

For the first time, for welded joints of aluminum-lithium alloys obtained by laser welding and optimal post-processing, mechanical characteristics are achieved that are comparable to those for alloys in the state of delivery.

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