Methods for forecasting and control of the phase composition and residual voltage in Al-Cu-Li alloys in friction mixing welding

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Abstract. One of the main directions for reducing the weight of structures of aerospace engineering products is the use of aluminum-lithium alloys, which have unique characteristics of strength, rigidity and fracture toughness [1–3]. Nevertheless, the manufacture of large-sized welded structures from high-strength aluminum-lithium alloys is associated with serious problems due to their softening under the influence of the thermal cycle of fusion welding, for which the joint strength coefficient (the ratio of the weld strength to the strength of the base material) is below 60% [4, 5]... It is possible to increase the operational characteristics of welded joints through the use of new effective technological processes, such as friction stir welding (FWW) [6].

1. Introduction
The FTP process provides numerous advantages due to the fact that welding takes place without melting the metal. First of all, these are low residual stresses and, accordingly, small deformations and distortion of the shape of the workpiece, good dimensional stability and reproducibility of the process, no loss of alloying elements, fine microstructure, and no cracks [7]. Welded joints of sheets from alloys with lithium, made by STP, allow increasing the coefficient of strength of the joint from 55–60 %, typical for fusion welding to 70–75 % [8]. The FTP process is characterized by a combination of deformation and thermal effects, which form a complex structural-phase state [9, 10]; therefore, it is important to develop methods of quantitative phase analysis, which make it possible to assess the volumetric transformation effects and predict the level of residual stresses in welding and smelting ingots and thermomechanical processing.

2. Materials and research methods
The study was carried out on welded joints of plates made of a pressed panel of alloy V-1469 (Al-3.8Cu-1.3Li-0.5Mg) 10 mm thick. To weld the plates, a tool was used, the geometry of the working part of which had a conical shape with a flat bottom part 5 mm in diameter, and a wide part of 11 mm in diameter. The winding pitch on the working part is 1.25 mm, depth is 1.0 mm. Cross-section of the working part of a circle with three milled grooves located at an angle of 120 to each other with a width variable in height from 2.0 to 4.0 mm. Tool shoulder diameter is 25 mm, double-row winding with a depth of 0.4 mm.

X-ray structural studies were carried out on a DRON-4 diffractometer. The lattice periods of the α-solid solution were measured in filtered CuKα radiation and using the (511)/(333) reflection with a
diffraction angle $\theta \sim 80–810$. Residual stresses were determined by the “$\sin 2\Psi$” method. The lattice parameter values corrected for residual stresses were used to estimate the amount of intermetallic T1 (Al2CuLi) and $\delta'$ (Al3Li) phases.

3. Research results and discussion

The ratio of intermetallic phases in Al-Cu-Li alloys was calculated from the balance equations for the elemental and phase composition:

$$
100 X_{Al}^0 = X_{Al}^{\alpha} W_{\alpha} + X_{Al}^{T_1} W_{T_1} + X_{Al}^{\delta'} W_{\delta'}
$$

$$
100 X_{Cu}^0 = X_{Cu}^{\alpha} W_{\alpha} + X_{Cu}^{T_1} W_{T_1}
$$

$$
100 X_{Li}^0 = X_{Li}^{\alpha} W_{\alpha} + X_{Li}^{T_1} W_{T_1} + X_{Li}^{\delta'} W_{\delta'}
$$

where: $X_{Al}^0, X_{Cu}^0, X_{Li}^0$ – concentration of Al, Cu and Li in the alloy, respectively (wt.%); $W_{\alpha}, W_{T_1}, W_{\delta'}$ – mass % of $\alpha, T_1, \delta'$-phases, respectively; $X_{Al}^{\alpha}, X_{Cu}^{\alpha}, X_{Li}^{\alpha}, X_{Cu}^{T_1}, X_{Li}^{T_1}, X_{Al}^{\delta'}, X_{Li}^{\delta'}$ – concentrations of Al, Cu and Li in $\alpha, T_1 \text{ and } \delta'$-phases, respectively.

The solution of system (1) gives the following relations for the $\alpha$-solid solution, T1 and $\delta'$-phases [11, 12]:

$$
W_{\alpha} = \frac{(X_{Li}^{\delta} - X_{Li}^{T_1})(X_{Al}^{0} X_{Cu}^{T_1} X_{Cu}^{0} X_{Al}^{T_1}) - X_{Al}^{\delta'} X_{Cu}^{0} (X_{Li}^{\delta} - X_{Li}^{T_1})}{(X_{Li}^{\delta} - X_{Li}^{T_1})(100 X_{Cu}^{0} - X_{Cu}^{\delta'} X_{Cu}^{T_1} X_{Li}^{\delta} - X_{Al}^{\delta'} X_{Cu}^{0} (X_{Li}^{\delta} - X_{Li}^{T_1}))} \times 100
$$

$$
W_{T_1} = \frac{100 X_{Cu}^{0} - X_{Cu}^{\delta'} W_{\alpha}}{X_{Cu}^{T_1}}
$$

$$
W_{\delta'} = 100 - W_{\alpha} - W_{T_1}
$$

The quantitative ratio of phases in alloys makes it possible to calculate volumetric and linear changes in dimensions during the precipitation or dissolution of intermetallic phases [12, 13].

The specific volume, $V_{\alpha}$, of a single-phase solid solution based on aluminum is:

$$
V_{\alpha} = \frac{N_{A} a_{\alpha}^3}{A_{\alpha} n}
$$

where $N_{A}$ – Avogadro's number $6.022 \times 10^{23}$ (mol$^{-1}$); $a_{\alpha}$ – lattice distance at 25 °C (cm); $A_{\alpha}$ is the atomic weight; $n$ is the number of atoms per unit cell $= 4$.

The specific volume of intermetallic phases is determined from the ratio:

$$
V_{\delta(T1)} = V_{u.c} / M_{u.c} = 1/\rho_{\delta(T1)}
$$

where $V_{u.c}, M_{u.c}$ – respectively, the volume and mass of the unit cell of the intermetallic phase, $\rho_{\delta(T1)}$ – the density of the intermetallic phase.

The specific volume of a mixture can be calculated through the specific volumes of the phases and their content in mass percent according to the rule of mixtures:

$$
V_{m} = \frac{W_{A} V_{A} + W_{B} V_{B}}{100}
$$

where $W_{A}$ – mass % of phase A; $V_{A}$ is the specific volume of phase A; $W_{B}$ – mass % of phase B; $V_{B}$ is the specific volume of phase B, etc.

The relative change in volume is:

$$
\frac{\Delta V}{V_{1}} = \frac{V_{2} - V_{1}}{V_{1}}
$$
Figure 1 shows how the difference between the amount of intermetallic phases in the base material and the mixing zone changes. It can be seen that the distribution of the phase composition changes over the weld cross section, and at the same time these changes are non-monotonic (figure 1).

![Graphs showing phase composition distributions](image)

**Figure 1.** Distribution of the phase composition in the cross section of the welded joint on the surface (a) and at a distance z = 2.5 mm (b), 3.5 mm (c) and 6 mm (d) from the surface: X is the distance from the center seam.

This is clearly seen in figure 2, which shows the values of the difference ($\Delta_\delta$, $\Delta_{T_1}$) between the amount of intermetallic phases in the base metal (BM) and in the center of the mixing zone (ZP, X = 0 in figure 1) for different sections of the welded joints:

$$\Delta_\delta = W^{3\Pi}_{\delta} - W^{BM}_{\delta}$$

$$\Delta_{T_1} = W^{3\Pi}_{T_1} - W^{BM}_{T_1}$$

The most pronounced gradient of the phase composition is observed in the subsurface layers, regardless of whether from the front or rear surface, figure 2. The least pronounced gradient is observed in the central zone. This result is of considerable interest, since it demonstrates the capabilities of the quantitative phase analysis technique for objectively assessing the thermomechanical effect of FSW modes on the phase composition, and, consequently, on the properties of alloys, and, as a result, on the optimization of the welding process and modes of corrective heat treatments.

4. Conclusions

1. A method of quantitative phase analysis has been developed, which makes it possible to determine the ratio of intermetallic $T_1$ and $\delta'$-phases in alloys of the Al-Cu-Li system and, on this basis, to evaluate the volumetric effects of phase transformations in different zones of the welded joint.
2. The technique has been successfully tested on an FSW joint made of alloy V-1469, for which it has been shown that the technique is effective for optimizing the welding process and modes of corrective heat treatments.

![Figure 2. Gradient of phase composition in the cross section of the welded joint depending on the distance from the surface: \( t / T \) – distance from the surface in fractions of thickness (T).]

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