TECHNOLOGICAL CAPABILITIES FOR IMPROVEMENT OF RELIABILITY OF WELDED JOINTS ON ALUMINIUM-LITHIUM ALLOYS

T.M. LABUR
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Technological capabilities for increasing strength and fracture toughness of welded joints on aluminium-lithium alloys are considered in terms of ensuring the reliability and safe operation of structures. It is shown that the use of low heat input in welding and new modified welding wires with a decreased content of harmful impurities provides a sufficient level of mechanical properties in all structural zones of the welded joint.

Keywords: *arc welding, aluminium-lithium alloys, welded joints, aerospace engineering, strength properties, fracture resistance, product reliability, technological operations*

Metal scientists, technologists and designers for a long time tried to create all-welded structures for aerospace engineering instead of the regular built-up-riveted structures. This predetermines the urgent need to develop high-strength readily weldable aluminium alloys with a high specific strength. Development of structures with extensive application of various assembly-welded and monolithic elements was also required, namely press panels, wing spars and connector profiles, and large-sized sheet stampings for parts of the wing and fuselage.

Solving these tasks was made possible by appearance of a new class of high-strength lithium-containing aluminium alloys: Al–Li–Mg (1420, 1421, 1423, 1424) and Al–Li–Cu (1450, 1451, 1460, 1461, 1463, 1464, 1468) with the ultimate strength of 400–420 and 500–550 MPa, respectively, which are readily welded by various welding processes [1–8]. This was promoted by a unique combination of properties, characteristic for aluminium-lithum alloys, namely high values of strength and modulus of elasticity at a low specific weight that distinguishes them from the traditional aluminium alloys. A comparatively low rate of fatigue crack growth in the alloys, high values of the critical coefficient of stress intensity, low-cycle fatigue life, resistance to stress corrosion cracking, layer and intercrystalline corrosion, allow including them into the class of the most promising materials for development of samples of new equipment with improved tactico-technical parameters.

These features of aluminium-lithium alloys were used in development of an all-welded aluminium airplane, where pressurized load-carrying tank compartments of a frame structure were applied [3–6]. However, manufacturing and operation revealed individual short-comings both of the structure proper and of 1420 alloy, in particular, its low ductility, which were later on leveled out by adding rare-earth metals to the alloy composition, development of a new technology of melting and pouring, as well as application of rational design of specific parts and components.

High specific strength and increased modulus of elasticity of aluminium-lithium alloys allow reducing the structure weight by 8 –15 %. New design solutions provided a reduction of the quantity of reinforcing elements and sealing materials that reduces the weight by another 12 %. Such an effect of aluminium-lithium alloy application in aerospace engineering products allowed an essential improvement of technico-economic characteristics of the product that is quite important to reduce fuel costs and improve flight characteristics [2].

The objective of this work is generalization of the published investigation results on the influence of thermal cycle of welding on the structure and properties of joints of aluminium-lithium alloys and substantiation of technological methods of improvement of welded structure reliability in operation.

By now the technological difficulties of producing sound welded joints which are related to metal softening, formation of a heterogeneous structure in different regions, as well as internal defects such as pores and oxide films, have been overcome [3]. Results of investigation of the features of formation of welded joints on aluminium-lithium alloys in fusion welding were the basis for development of ingenious welding technologies, application of which provides tighth welds with high values of physico-mechanical properties [3, 7, 8]. Strength of arc-welded joints is equal to 75–85 % of base metal strength level. Application of electron beam welding allows making joints of the strength close to base metal. In this case, the length of the HAZ is essentially reduced compared to arc-welded joints. Improvement of properties is noted not only in the weld metal, but also in the joint weakest zone — on the boundary of its fusion with the base metal that is due to formation of a fine-crystalline structure in the weld. Nonetheless, it was found [9] that metal overheating during welding leads to lowering of the level of critical coefficient of stress intensity to a greater degree, particularly in the zone of alloys, compared to the traditional alloys of Al–Mg–Mn and Al–Cu–Mn alloying systems (Figure 1, *a*, *c*). Development of embrittlement of aluminium-lithium alloys in the heating zone increases the probability of crack initiation in the joint in service. The problem of protection of welded structures from premature failure, which is one of the most urgent for the national economy, is closely related to cost issues. Metal loses at failure amount to billions of hryvnias per year [1]. In this connection development of new products for aerospace engineering should take into account the influence of technological factors of welding on the features of structure formation in different zones of aluminium-lithium alloy joints, and causes leading to metal embrittlement. Development and realization of a package of measures will allow increase of the level of strength and fracture toughness of welded joints and improvement of their performance under diverse operating conditions.

Formation of conditions for accelerated initiation and propagation of a crack near brittle phase inclusions is due to characteristic partial melting of structural components that arises in aluminium alloys under the influence of non-equilibrium solidus temperature in welding. Formation in intergranular space of extended brittle regions from oversaturated and intermetallic phases hindering plastic deformation of metal, is associated with its long-time soaking at high temperatures (673–773 K) that accompany the welding process. The latter leads both to intensive development of structural heterogeneities, and distribution of alloying elements and impurities contained in various zones of welded joints, and to their segregation along grain boundaries. With increase of volume fraction of such regions in the welded joint structure, an increase of the level of stress concentration is noted, that is indicated by formation of flat sections of the relief along the boundaries of crystallites and grains in the fractures of broken samples [10–15]. This is accompanied by lowering of fracture resistance characteristics: nominal breaking stress σ_{br} from 340 to 265 MPa, critical coefficient of stress intensity K_C from 29.5 to 21.5 MPa$\sqrt{m}$, critical crack opening displacement δ_C from 0.14 up to 0.03 mm, initiation energy J_C and specific work of crack propagation (SWCP) from 5.8 and 7.5 to 2.5 and 3.8 J/cm^2 [14].

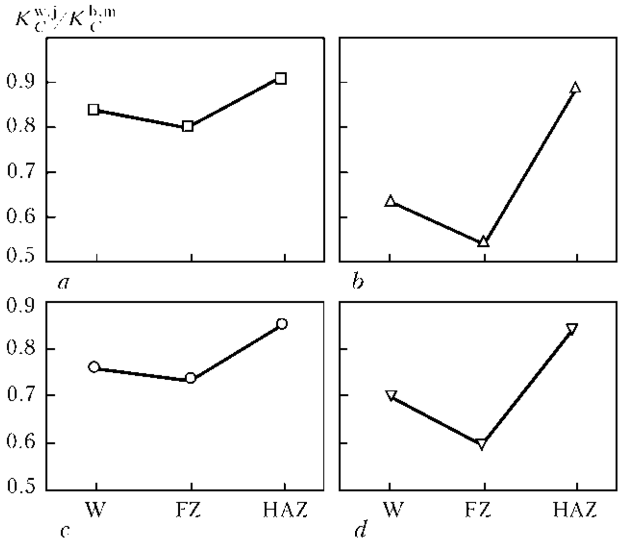

Figure 1. Comparison of crack resistance $K_C^{w.j}$ of different zones of welded joints of aluminium-lithium alloys made by conventional nonconsumable-electrode arc welding and base metal $K_C^{b.m}$: *a* — Al–Mg–Mn; *b* — Al–Li–Mg; *c* — Al–Cu–Mn; *d* — Al–Li–Cu

Increase of stress concentration as a result of the presence of geometrical or mechanical notch, including a fatigue crack, reduces by 40–55 % the value of the coefficient of stress intensity K_C, determining the fracture conditions [10]. Range of scatter of the values of this fracture resistance index varies depending on the radius of stress raiser sharpness and stress-strain state of welded joint structural zones. In the weld metal it is 10 %, and in the fusion and heat-affected zones — 20–25 %, that differs essentially from Al–Mg and Al–Cu system alloys without lithium. Non-uniform influence of the stress raiser on K_C fracture toughness value in the zones of welded joints is due to varying amounts of lithium-enriched phases, precipitating along the boundaries of weld crystallites and base metal grains during welding heat impact. This is particularly pronounced in samples of joints, in which the notch tip is combined with the weld to base metal fusion line (Figure 2). The found dependence is related to the features of formation of the structure of this joint zone under the conditions of metal solidification after heating in welding. In arc welding processes thickened grain boundaries, pres-

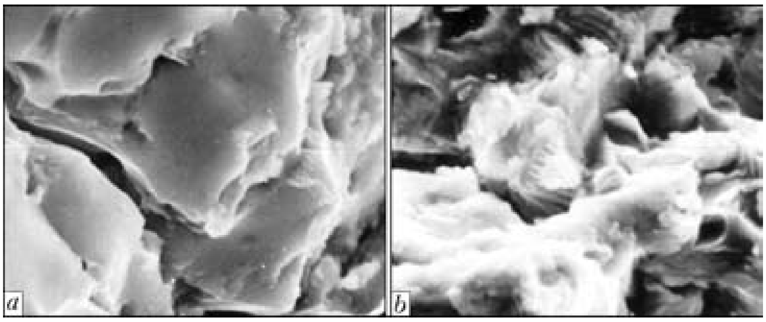

Figure 2. Microstructures (×500) of fracture surface of metal on fusion boundary of arc-welded joints: *a* — 1421 alloy; *b* — 1460

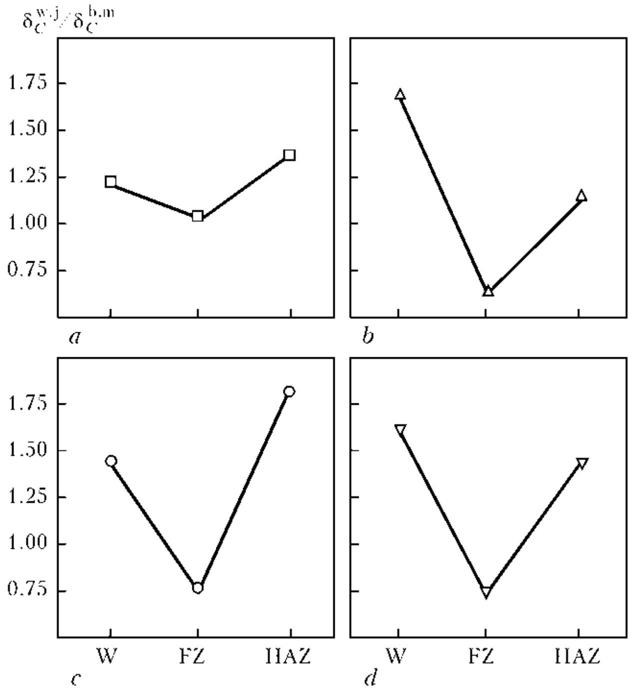

Figure 3. Comparison of the value of critical crack opening displacement $\delta_C^{w.j}$ in different zones of welded joints of aluminium-lithium alloys and base metal $\delta_C^{b.m}$: *a* — Al–Mg–Mn; *b* — Al–Li–Mg; *c* — Al–Cu–Mn; *d* — Al–Li–Cu

ence of their triple junctions and a considerable amount of partially melted phases are found in the fusion zone structure. Increased density of secondary phase precipitates and coarsening of intermetallic phase inclusions in the HAZ metal lead to formation of regions of unfavourable structure in the form of individual clusters or frame following the grain boundaries. In electron beam welding a predominantly polyhedral structure with rare inclusions of partially-melted phases is found [9].

Dimensions and position of phase inclusions in the intergranular space, particularly on the boundary of weld fusion with the base metal, influence stress concentration and volume fraction of brittle regions, i.e. conditions of crack initiation in welded joints of aluminium-lithium alloys. Presence of such structural sections along the grain boundaries, alongside the shear bands forming during semi-finished product manufacturing, limits plastic deformation and promotes an increase of the stress-strain state in welded joints. Shear bands, being the areas softened by deformation localization, as though predetermine the brittle mode of crack initiation in the HAZ metal in the regions of contact of the slip band with the boundary of the crystallite or grain. Total action of applied stresses and local stress concentration in the vicinity of the phases and shear bands cause intensive crack initiation both across the body, and along the boundary of contact with the matrix (see Figure 2).

Values of crack initiation energy (*J*-integral) of aluminium-lithium alloys 1421, 1460 and their welded joints

Alloy	Studied zone	*J*-integral, J/cm^2
1421 (Al–Li–Mg)	BML	3.6–4.4
	BMT	2.5–3.8
	W	4.9–6.8
	FZ	1.5–2.9
	HAZ	2.8–3.6
1460 (Al–Li–Cu)	BML	4.0–5.6
	BMT	2.5–3.8
	W	5.2–6.7
	FZ	2.9–3.4
	HAZ	4.2–5.7

Note. BML and BMT — base metal of longitudinal and transverse orientation relative to rolling direction, respectively; W — weld metal; FZ — fusion boundary metal; HAZ — HAZ metal at 5 mm distance.

A similar dependence of fracture resistance on structure condition in welded joint zones is also traceable by a characteristic change of critical crack opening displacement δ_C and its initiation energy (*J*-integral). As is seen from Figure 3 and the Table, the line of weld fusion with the base metal features minimum values of fracture resistance compared to other structural zones of the welded joint that should be taken into account in design of critical products. K_C and δ_C values for this joint zones are equal to 23 MPa$\sqrt{m}$ and 0.004 mm, respectively. J_C and SWCP values, reflecting the features and nature of crack initiation and propagation, depend on chemical composition of alloys being welded. In 1421 alloy (with magnesium), they are equal to 3.1 and 4.5 J/cm^2, respectively, and copper-containing alloy 1460 has higher values of J_C (4.0 J/cm^2) and SWCP (6.2 J/cm^2). Established regularities of the change of properties of aluminium-lithium alloy joints are indicative of a strong influence of structural state of the boundaries of weld crystallites and base metal grains in the welding heating zone on the strength of adhesion of the matrix with phase precipitates determining the metal susceptibility to brittle fracture.

Presence of stress raisers in welded joint metal is particularly hazardous for difficult conditions of structure operation, when the action of turbulent air flow results in a change of the loading pattern or deformation rate, while increase of the flight altitude leads to a temperature change. The above service factors lead to an additional loss of metal ductile properties in the structure, although the joint strength can increase up to 400–420 MPa here, as a result of strain or low-temperature hardening [11–15]. Degree of lowering of ductility and fracture toughness depends on the volume fraction of brittle local regions formed in the intergranular space at heating, and level of working stress. Reaching a critical value, they lead to crack initiation under the operation conditions and determine the subsequent nature of its propagation (in keeping with Griffith theory [1]).

Increased susceptibility of aluminium-lithium alloy joints to embrittlement is attributable to a high degree of their alloying compared to other high-strength base alloys of Al–Mg–Mn and Al–Cu–Mn alloying systems that results in an excess amount of phases forming in the intergranular space. Their presence and dimensions prevent relaxation of alloy stresses during plastic deformation that leads to stress accumulation and formation of an unfavourable dislocation structure of complanar type near the phases, revealed after sample fracture at testing. Brittle fracture in this case occurs as a result of running of even though intensive, yet highly localized plastic flow that may run at a very low level of shear stresses, and may lead to development of powerful and hazardous dislocation clusters creating the conditions for crack initiation [1]. This feature of aluminium-lithium alloys is attributed to lithium susceptibility to plane slipping during its redistribution along the grain boundaries that results in ductility lowering. Lowering of lithium content in the alloy (to 1.7–1.9 wt.%) promotes 1.5 times increase of such a ductility characteristic as relative elongation [2].

Procceding from experimental studies [9] it was found that favourable thermophysical conditions of welding are provided by processes featuring minimum heat input: pulsed arc $(10–13)\cdot10^5$ J/m) or electron beam $(1.2–1.4)\cdot10^5$ J/m) welding that allows 4 and 10 times reduction of the extent of the regions, respectively, in which brittle intecrystalline interlayers are present in the welds and inergranular interlayers in the HAZ metal, as well as microvoids in the fusion zone. Such a state of welded joint structure provides an improvement of metal resistance to crack initiation. Value of σ_{br} parameter in individual zones of the joints in this case rises by 70–100 MPa, and that of K_C — by 20–25 %. Improvement of metal quality leads to an increase of properties not only in the weld metal, but also in the weakest zone of welded joints: on the boundary of joint fusion with the base metal. Reduction of metal sensitivity to stress raisers creates prerequisites for ensuring reliabile performance of welded parts and components from aluminium-lithium alloys in fabrication of load-carrying panels, compartments and fuselage structure as a whole. Replacement of riveted overlap joints by butt joints allows reducing the number of transverse welds by application of extended blanks.

Application of modes of two-step annealing with intermediate deformation of up to 3 % also has a positive influence on the level of physico-mechanical properties of aluminium-lithium alloys [15]. Such a technological operation ensures formation of a favourable alloy structure that has an influence on the level of fracture resistance characteristics. Introduction of straightening after quenching suppresses the process of brittle phase coarsening, accelerating dissolution of strengthening phase δ, and somewhat reduces its dimensions, thus increasing the value of fracture toughness parameter K_C by 10 %.

Improvement of reliability parameters is achieved also by optimization of weld metal composition by addition of scandium in the range of 0.4 to 0.6 % to filler wire composition [16–18]. Here, not only the susceptibility of aluminium-lithium alloys to hot cracking is decreased, but also high fracture toughness values are ensured: σ_{br} = 310–320 MPa, K_C = 25–28 MPa$\sqrt{m}$, σ_C = 0.05–0.07 mm, J_C = 4–6 J/cm^2, SWCP = 8–10 J/cm^2. Level of weld metal strength rises by 20 %, and relative elongation is equal to 7 %. This is promoted by formation of fine-crystalline and subgrain structure of welds due to complete dimensional-structural similarity of dispersed particles of scandium aluminide Al_3Sc with the matrix [3]. Scandium presence in the base metal decelerates the recrystallization processes, running in welding of aluminium alloys that reduces the length of the softening zone. The noted effect is very important for fabrication of welded structures of aerospace engineering. It allows lowering the strictness of specifying the temperature-time conditions of welding, limiting the aluminium-lithium alloy susceptibility to softening, as the HAZ extent depends not only on the welding process, but also on the alloy composition. As shown by investigations [9–12], the action of welding heating on the strength and toughness of welded joint metal is manifested to a smaller degree in alloys containing magnesium as the main alloying component than in alloys with copper. This is due to stronger ability of magnesium, compared to copper additive, to accelerate the processes of precipitation of strengthening phase δ′, and thus increasing their density in the metal bulk [1]. It should be noted that alloys of 1460 type, alloyed with copper, perform satisfactorily at cryogenic temperatures in contact with liquid oxygen, hydrogen and helium [12]. Strength and ductility characteristics of the alloys and their welded joints here rise with temperature lowering. Such a feature of the alloys allows them to be used in welded structures of space flying vehicle fuel tank of a complex geometry with provision of high service properties of welded joints and their leak-tightness. Use of an alloy of 1460 type in the structure of the tank of US Delta rocket allowed the tank weight to be reduced from 2259 to 1430 pounds [13]. Improvement of welded joint reliability is further promoted by reduction of volume fraction of intermetallic phases in the alloy structure, which contain impurities of alkali and alkali-earth elements (sodium, calcium, barium and potassium). Even thousandths of a percent of these elements in the alloy composition have an adverse effect on welded joint properties as a result of lowering of melting temperature of the phases precipitating along the grain boundaries, making them hazardous for fracture development. Being at the grain boundaries, they, because of their high chemical activity relative to aluminium, reduce the metal surface energy on the inner free surfaces, for instance, on the edges of present microcracks, and thus increase the metal susceptibility to embrittlement and crack propagation [19, 20]. Here, the level of ductility and fracture toughness characteristics decreases by 30–40 %, whereas no deterioration of strength is noted. Limitation of the quantity of impurities in the alloy composition to 0.01 % reduces the adverse influence of boundaries of crystallites and grains on the processes of crack initiation, increases the quantity of tough regions of fracture relief, thus increasing level of σ_{br} by 20 % and K_C level by 40 % at δ_C = 0.05 mm, J_C = 4 J/cm^2, SWCP = 5.2 J/cm^2. Maximum effect is achieved only at uniform distribution of intermetallic phases in the metal volume. Mode of joint fracture in the fusion zone changes from intercrystalline to transcrystalline.

Generalizing the results of investigations of welded joints of aluminium-lithium alloys [1, 2, 9, 10, 18–20], it can be stated that the condition of grain boundaries in structural zones forming under the influence of thermal cycle of welding, determines the level of physico-mechanical properties and mode of joint fracture. Condition of grain boundaries depends on the quantity of alloying elements and impurities, presence of phase clusters located along the rolling line, in the initial metal. Adverse influence of welding is manifested only in the case of development of extended regions of the weld and HAZ with an unfavourable structure forming during metal heating with a high heat input. To prevent such a phenomenon in aluminium-lithium alloy welding, it is necessary to strictly specify the heat input, using pulsed arc welding modes or electron beam (laser) welding, which are characterized by a high concentration of applied heat. In this case welded joints have the necessary values of strength and fracture toughness that is important for aerospace engineering products in operation under extreme conditions, including a wide temperature range (20–500 K). As a result, alongside reduction of product weight, also the task of provision of good adaptability of the structure to fabrication, as well as reliable failure-safe operation during an extended operation period, is solved. This is confirmed by the available cases of application of aluminium-lithium alloys and their welded joints in the structure of load-carrying sheaths of aircraft, helicopters and rocket fuel tanks for reusable space vehicles [3–6].

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