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ANALYSIS OF THE PROPERTIES AND FEATURES OF HIGH-STRENGTH DEFORMABLE ALUMINIUM ALLOYS OF Al–Li, Al–Cu–Mn SYSTEMS USED IN THE AEROSPACE INDUSTRY IN MANUFACTURE OF WELDED STRUCTURES (REVIEW)

V.I. Zagornikov

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

The paper presents the main directions of development in the field of promising aluminium alloys. New generation alloys with improved chemical composition, technologies of manufacture and heat treatment of semi-finished products are considered. The question of the relationship between the structure of the alloys and their operational properties, the influence of heat treatment modes and alloying on mechanical properties and weldability of aluminium alloys in order to obtain the specified predicted operational properties is highlighted. The results of the use of aluminium alloys in aviation and space technology are described. A review of commercial deformable alloys of Al–Li and Al–Cu–Mn system, and comparative characteristics of weldability of various promising aluminium alloys (1460, V-1469, 1201 and their analogues 2090, 2195, 2219) is conducted.

KEY WORDS: heat treatment, weld alloying, weldability assessment, measures to prevent porosity, promising methods of producing welded joints, electron beam welding (EBW)

INTRODUCTION

The growth rate of commercial aircraft and rocket construction in Ukraine and in the world dictates the pace of introduction of modern and innovative technologies and materials. One of the most important tasks currently facing the aerospace industry is improving the equipment weight efficiency and its strength, which will allow increasing the weight of the orbited payload.

Modern requirements to materials are becoming ever more stringent. However, deformable aluminium alloys remain the basic structural materials for advanced aerospace products due to their low density, set of service properties, good adaptability-to-manufacture, weldability and mastering in the metallurgical production. In addition to a significant weight reduction, these alloys should have higher specific and service properties, which will allow application of more efficient design solutions, such as electron beam, laser, friction stir, and automatic argon-arc welding using new filler materials.

For flying vehicle structures not the absolute, but specific values of strength properties (σ_t/ρ, $\sigma_{0.2}/\rho$) are important. Therefore, owing to their high specific strenght the dispersion-hardening alloys of Al–Li and AL–Cu–Mn system are widely used in the structures of space and aviation technology products, in particular products for cryogenic applications, namely rocket fuel tanks, fuselage skins and load-carrying elements of aircraft design. Alloys not prone to delayed fracture and having a high ductility of base metal at liquid helium and hydrogen temperature are used for operation under the cryogenic conditions [1–3].

Despite all the advantages of the developed alloys, there is the task to improve the crack resistance characteristics at preservation of the high level of strength and corrosion resistance. Their composition, structure, modes of manufacture, in particular, of thermomechanical treatment, are constantly improved in keeping with the growing requirements to the structures. This task is solved through development and introduction of advanced superlight high-strength materials and their joining technologies.

The objective of this work consists in formulation of modern requirements to properties of semi-finished products from deformable aluminium alloys 1460, V-1469, 1201 and their analogs 2090, 2195, 2219, and substantiation of the priority of application of a deformable alloy of 1201(2219) type, when producing sound welded joints, using EBW in the structures of aerospace products.

DISCUSSION OF PROBLEMS IN THE FIELD OF THE TECHNOLOGY OF HEAT TREATMENT AND WELDING OF ALUMINIUM ALLOYS OF Al–Li AND Al–Cu–Mn SYSTEM FOR AEROSPACE PRODUCTS

With development of aerospace engineering, the following requirements are made to selection of the structural material:

● the alloy should have a sufficient level of strength and service life characteristics;

● high adaptability-to-manufacture and energy saving in metallurgical production;

● possibility of various kinds of semi-finished products;

● adaptability-to-manufacture in production of parts and assembly of various structure components, also with welding application;

● the alloy should not contain any highly toxic components (cadmium, lead, mercury, beryllium) — elements which evaporate during welding.

The aluminium alloy properties can be improved both when changing their composition, and a result of application of new technologies of their production and treatment. To ensure optimal mechanical properties, depending on operating conditions (normal — cryogenic temperature) there is a certain mode of aging at heat treatment for each type of semi-finished products. Here, a certain phase composition forms in the metal structure. Precisely regulated deformation after quenching in combination with a certain mode of final aging should ensure the required set of physicomechanical properties.

The considered deformable structural aluminium alloys, mainly, are aluminium alloys with four components: Cu, Mn, Mg, Zn. Li, Sc, Zr and Ag were relatively recently added to them (Table 1).

All the abovementioned components were selected by one feature: they have the highest solubility in solid aluminium, compared to other known elements. It abruptly decreases with temperature lowering, resulting in intermetallic phase precipitation at cooling of alloys with these components from the solid solution, and their dissolution at heating. This phase transformation (the only one in solid aluminium alloys) opened up the possibility of significantly influencing the alloy structure and properties through heat treatment. The alloys have a high level of properties after strengthening heat treatment (quenching and aging), when the alloy matrix is a solid solution strengthened by dispersed particles of the intermetallic phases, precipitating from the solid solution at aging. This applies to alloys of all the systems, i.e. the strengthening mechanisms of all the alloys are the same: solid solution treatment + dispersion hardening. The difference between the considered alloys is determined by the composition, crystalline structure and properties of the dispersed particles of intermetallics, precipitating from an oversaturated solid solution, on which the strengthening effect depends. The main property of these particles is a very high hardness, compared to the matrix. Secondary dispersed precipitates of these intermetallic phases determined the high level of strength characteristics, achieved for aluminium alloys and the level of their applicability for critical structures [4].

As natural aging does not cause any changes, after quenching the semi-finished products are subjected to artificial aging. It eliminated the need to regulate the time interval between quenching and aging [5].

The purpose of aluminium alloy aging usually consists in an additional increase of the quenched alloy strength. To achieve maximal strength of the heat-hardenable alloys, it is necessary to obtain by regulated heating a certain intermediate structure corresponding to initial stages of decomposition of the oversaturated solid solution.

A structure, which combines clusters (Guinier–Preston zones) corresponds to the initial stages of decomposition of the oversaturated solid solution. These clusters have the appearance of platelike precipitates from the solid solution uniformly distributed over the grain as fine acicular inclusions, as well as along grain boundaries in the form of large flakes. At this stage, no processes of coagulation (coarsening) of strengthening phase particles are observed.

Aging of commercial aluminium alloys is conditionally divided into low-temperature (20–140 °C) and high-temperature (140–220 °C) modes. The products of decomposition of the oversaturated solid solution at low-temperature aging usually are coherent dispersed or partially coherent precipitates, homogeneously distributed in the grain volume. In some aluminium alloys (Al–Cu–Mn) preparation to decomposition and initial decomposition stages occur only at heating of the

Table 1. Chemical composition of alloys of Al–Cu–Li and Al–Cu systems (1460, V-1469, 1201 and their analogs 2090, 2195, 2219)

Alloy grade	Weight fraction of elements, %									
	Cu	Li	Zr	V	Ti	Mn	Sc	Mg	Ag	Si	Fe
1460 (USSR)	2.6–3.3	1.9–2.3	0.1	–	0.1	0.05–0.1	0.06–0.1	0.06–0.1	–	—	—
2090 (USA)	2.4–3.0	1.9–2.6	0.1	–	0.15	0.05	–	0.25	–	—	—
V-1469 (Russia)	3.2–4.5	1.0–1.7	0.02–0.26	–	0.05–0.07	0.05–0.08	0.02–0.28	0.01–0.5	0.45	—	—
2195 (USA)	3.7–4.3	0.8–1.2	0.12	–	0.1	0.25	–	0.25–0.8	0.25–0.6	—	—
1201 (USSR)	5.8–6.8	–	0.1–0.25	–	0.02–0.1	0.20–0.40	–	0.02	–	0.20	0.30
2219 (USA)	5.8–6.8	–	0.1–0.25	0.05–0.1	0.02–0.1	0.20–0.40	–	0.02	–	0.20	0.30

quenched alloy up to temperatures, usually in the range of 100–200 °C. The purpose of this heating is thermal activation of the diffusion processes.

This is the stage, which ensures the maximal strength properties (T1), or artificial aging modes with regulated softening, compared to T1 mode – T2 and T3 modes, compared to the aging stage, which provides maximal strengthening (achieving maximal yield limit). States T2 and T3 are usually realized through two-step aging. In aging modes, corresponding to the ascending branch of the strengthening curve, an abrupt lowering of the corrosion cracking resistance is possible. Such a phenomenon is observed, in particular, in alloys of Al–Cu and Al–Cu–Mg systems [6].

Without experiments it is impossible to predict the specific structure, providing maximal strengthening, which a particular alloy should have. The answer depends on the decomposition stages, which can occur in this alloy at the given aging temperature, on the precipitate structure, density of each type of precipitates and other factors.

Two main ways to produce an optimal set of properties required for reliable service of high-strength heat-hardenable aluminium alloys have emerged:

1. Increase of the alloy purity as to the main metal impurities (Fe and Si), i.e. lowering the admissible level of iron and silicon impurities in the alloys. In the majority of aluminium alloys up to 0.5 % Fe and up to 0.5 % Si are allowed to GOST 4784–74. Lowering the admissible content of iron and silicon to 0.1–0.3 % and even better to hundredths of a percent leads to an abrupt reduction of the volume fraction of insoluble intermetallic phases [Al_3Fe, α(Al–Fe–Si), α(Al–Fe–Si–Mn), etc.] and considerable increase of fracture toughness. The alloy other properties (σ_t, $\sigma_{0.2}$, δ and σ_{cr}, exfoliating corrosion) change only slightly. In this connection, higher-purity alloys began to be used recently.

2. Application of aging modes, causing a certain overaging of the metal. Such modes are called “softening” aging modes and for deformable alloys they are designated by numbers T2 and T3 (aging to maximal strength is denoted as T1 and quenching with subsequent natural aging as T); T3 corresponds to stronger overaging than T2. Compared to aging to maximal strength, softening aging, while leading to partial or complete violation of the coherence of strengthening phase precipitates and the matrix, and to their more homogeneous distribution, causes a certain lowering of the strength, but an essential increase of fracture toughness, resistance to stress corrosion and exfoliating corrosion [7].

Heat treatment allows achieving a great diversity of structures also in alloys, having no phase transformations in the solid state, but only in the case, when the initial nonequilibrium state was produced either during casting (during nonequilibrium crystallization), or by deformation. To achieve maximal strength, the following three kinds of heat treatment became widely accepted for aluminium alloys: annealing, quenching and aging, which allow implementing a balanced set of mechanical properties and heat resistance.

The following system of designations of the states of deformable aluminium alloys after strengthening treatment was accepted:

T1 — artificial aging in its pure form. It allows increasing the mechanical strength of the semi-finished products and finished products, particularly, if their machining is planned furtheron. Such a kind of treatment has a negative impact on duraluminium corrosion resistance and mechanical strength, and it is seldom used for it.

T2 — annealing. It allows relieving the casting and thermal stresses in the material, and improves its ductility, and it is used in the case, when the billet will be subjected to cold pressure processing.

T3 — quenching. It is applied for improvement of the alloy strength properties and for ensuring the required corrosion cracking resistance.

T8 — a state, in which the solution heat treatment is followed by cold working, and then by artificial aging. It is applied for products subjected to cold working, straightening or leveling to increase the strength.

T81 — it is applied for products, artificially aged after solution heat treatment, here the strength rises by approximately 1% of cold working deformation.

T87 — applied for products with approximately 7 % cold working deformation to increase the strength after solution heat treatment and further artificial aging.

T62 — it is applied for artificially aged products after solution heat treatment in O or F state. It is also used for products, the mechanical properties of which reach T62 state after heat treatment of products treated to any state.

Not less promising is the route of further improvement of strength, high-temperature strength, corrosion resistance and other service and technological characteristics through application of aluminium alloy doping by metals, which are poorly soluble or practically insoluble in solid aluminium, but which form various intermetallic compounds with aluminium [8].

ADVANTAGES OF 2219 ALLOY

Let us consider 2219 aluminium alloy. The advantages of 2219 alloy are improved mechanical properties of base metal and welded structures at temperatures well below zero (to –253 °C). The alloy has good values of tensile and yield strength, as well as good fatigue and creep fracture properties (to –315 °C). It can be easily worked by pressure. These properties remain unchanged after heat treatment. In George S.Marshall Center it was proved experimentally that structural 2219 aluminium alloy is sufficiently hardened so that the defects caused by nuclear and space radiation did not significantly affect its mechanical and physical properties, either at room ambient temperature and at elevated temperatures, below the accumulated doses of approximately 10^{22} particles s/cm^2 [9]. The possibility of receiving a dose of this order is extremely small, except for cases of pulsar action in immediate vicinity. The high resistance to elevated temperatures, hard vacuum, high-energy radiation and micrometeorites, which influence the characteristics of 2219 alloy surface through desorption and erosion processes, makes such an alloy highly promising for application as space vehicle skin.

The disadvantages of the abovementioned metal are as follows. Heating above 300 °C leads to strong softening, because of coarsening of the main phase of Al_2Cu strengthening agent. Moreover, the method of manufacturing wrought semi-finished products from ingots requires a complicated technology, which includes high-temperature homogenizing annealing, pressure treatment, heating of the semi-finished products above 500 °C for quenching in water and aging, which significantly increases the cost of the final product.

The wide range of possibilities for joining structural elements made from such an alloy should be noted. The 2219 alloy demonstrates the best weldability among aluminium alloys of 2xxx series, which is related to absence of magnesium and silicon as alloying elements in it. These elements form the ternary and quaternary eutectics with low melting temperatures and thus widen the alloy melting range. It is known that the wide range of melting temperatures, as the presence of phases with a low melting temperature, leads to weld cracking, but 2219 alloy does not have this drawback.

Considering the high value of the linear expansion coefficient and significant shrinkage of the crystallizing metal, alongside its low mechanical properties already at the temperature of 236.85–246.85 °C, the technology of aluminium alloy assembly and welding should envisage minimal welding strains and stresses. The process of welding and postweld heat treatment affects the deformational properties of 2219 alloy sheets [10, 11]. Minimal welding strains and stresses (2–4 times lower than in argon-arc welding) are achieved at single-pass electron beam welding of a large-sized structure, performed with a certain sequence of weld deposition [12]. In those situations, when quenching of the entire large-sized structure is not always admissible, because of the structure overall dimensions and deformations arising at heat treatment, application of narrow electron beam welds is indispensable.

These results show that 2219 is the most readily weldable and the least sensitive to changes in the welding procedures of all the heat-treatable high-strength aluminium alloys. At repeated heat treatment after welding the alloy steadily develops its strength, which is equal to tensile strength of the base metal. T81 and T87 annealing modes are recommended for components which remain in “as-welded” state. For components which are to be heat treated after welding, quenched alloys (without any additional treatment after manufacture) are recommended, due to their lower cost. Other characteristics, however, are also satisfactory. The recommended postweld practice is T62 for maximal strength and reducing distortions [13, 14].

THIRD GENERATION ALUMINIUM-LITHIUM ALLOYS

Over the recent years a decisive transition to aluminium-lithium alloys has been made in world cosmonautics. Compared to regular aluminium alloys, such as 2219, which is widely used in cryogenic tanks of space vehicles, as well as in unsealed structures, the aluminium-lithium alloys are characterized by a good combination of lower density with higher modulus of elasticity, good weldability, as well as mechanical properties superior to those of aluminium alloys without lithium.

Various factors influence the commercial alloy properties. The serviceability of aluminium-lithium alloys is determined chiefly by such service life characteristics as fatigue crack growth rate, coefficient of stress intensity in the crack tip (K_c, K_{ic}), low-cycle fatigue life, corrosion cracking resistance, and intercrystalline corrosion.

The most important factors having a great influence on the level of the abovementioned properties include:

- type of grain structure: degree of recrystallization, grain shape anisotropy, presence and density of precipitates on the boundaries of grains and subgrains, presence of near-boundary zones free from precipitates;
- cold tensile deformation between quenching and aging of the semi-finished products;
- artificial aging mode.

INFLUENCE OF GRAIN STRUCTURE ON THE ALLOY PROPERTIES

Semi-finished products with a predominantly recrystallized structure have higher characteristics of fracture toughness and crack resistance at somewhat lower strength properties, compared to nonrecrystallized structure. The main mechanism of fine-grained structure formation is recrystallization.

INFLUENCE OF COLD DEFORMATION BETWEEN QUENCHING AND AGING

A considerable effect of improvement of the strength properties, characteristics of fracture toughness and crack resistance, as well as corrosion resistance is observed in alloys of Al–Cu–Li and Al–Li–Mg–Cu systems at application of regulated cold tensile deformation of quenched semi-finished products before artificial aging. Such treatment results in increase of the density and dispersity of precipitates of heterogeneously strengthening phases, reduction of the width of near-weld zones, free from precipitates, and of the dimensions and number of stable phases on the boundaries.

INFLUENCE OF AGING MODES

Aluminium-lithium alloys can be aged to three states: underaged (soft mode), to maximal strength (aging "peak") and overaged. The optimal aging modes were developed to ensure the required combination of strength, ductility, toughness and corrosion resistance. It was found that for the majority of the alloys the high ductility and fracture toughness, combined with an average level of strength properties are achieved after low-temperature aging in the soft mode — underaged state. However, the best corrosion resistance is ensured as a result of overaging or aging to maximal strength. The best set of properties (mechanical properties at tension — fracture toughness) was achieved at a combination of high deformation (2–8 %) after quenching with low-temperature aging.

The enumerated features are taken into account together with the economic considerations at selection of the temperature-time modes, which ensure the maximal strength and hardness in commercial semi-finished products. When establishing the commercial modes, preference is given to those, which ensure an extended maximum on the aging curves [15]. As follows from the obtained results, the best level of mechanical properties is found in sheets after artificial aging at the temperature of 160 °C — ultimate strength and proof strength are not less than 25–35 MPa higher, compared to other studied modes.

Aluminium-lithium alloys have a special position among other aging aluminium systems. However, they have the disadvantage of a low ductility in the state of maximal strength. In order to overcome it, many studies of the influence of different factors on ductility and fracture characteristics of aluminium-lithium alloys have been performed. It was clarified that the causes for lower ductility and fracture toughness are the deformation heterogeneity; presence of zones free from the strengthening phase precipitates, appearance of pores near large particles and presence of natural admixtures such as K, Na, S, H_2, Fe, Si, forming low-melting eutectics on the grain boundaries, or precipitation of phases on them. Let us enumerate the main measures proposed for solving this problem (ductility increase). This is primarily aluminium-lithium alloy doping by copper and manganese, forming ternary phases with lithium and causing solid-solution strengthening. These phases, alongside the intermediate one, promote alloy strengthening at aging and its more homogeneous deformation. Doping aluminium-lithium alloys by zirconium and scandium serves the same purpose, which allows refining the microstructure and ensuring additional structural strengthening due to formation of ultrafine intermetallic particles. The forming phases effectively block the dislocation movement due to formation of Al_3Sc type phase, having a rather high discrepancy between the lattice and matrix parameters [16]. Modern aluminium alloys are multicomponent, so in case of their alloying by scandium one should take into account the strengthening influence of other elements, and essentially correct the modes of thermomechanical treatment of the alloys. There is also the method of two-step aging. Such aging causes a more homogeneous distribution of the precipitating phases and stabilization of the dispersed structure.

The possibilities of improvement of aluminium alloy strength by the traditional methods through alloying and aging have almost been exhausted. It should be noted, however, that not all the possible methods to improve the ductility of Al–Li alloys have been used. A combination of high characteristics of strength and fracture toughness in these alloys is due to minimal content of impurities, introducing a small quantity of rare-earth modifiers and addition of silver, and lower lithium content. The 2195 alloy containing silver is used to manufacture TSV fuel tanks, ensuring approximately 13 % weight reduction, compared to earlier applied 2219 alloy [17]. On the other hand, it was found that auxiliary additives of small quantities of lithium to aluminium alloys having controlled quantities of copper and magnesium ensure a high crack resistance and high strength of the material, which also has equivalent or improved resistance to fatigue crack propagation, compared to aluminium-copper-magnesium alloys. Increase of lithium content leads to improvement of aluminium strength properties. At up to 2 % lithium content the alloy strength is increased without ductility lowering, at further increase of lithium content the ductility drops abruptly. At up to 0.8 %

concentrations, lithium provides higher corrosion resistance of aluminium alloys, higher than that of pure aluminium. More over, lithium additives ensure an improvement of impact toughness at an increased level of strength. Thus, the combination of crack resistance and strength properties is significantly improved. This effect is unexpected, as lithium additives are known to lower the crack resistance in the traditional aluminium-copper-magnesium-lithium alloys [18].

In technical literature it was reported more than once that scandium is the most effective alloying component of aluminium alloys. The main obstacle in the path of expansion of its application is the high cost of scandium, which is added to the alloys in the form of Al–2 % Sc master alloy. At scandium application, its addition to aluminium alloys increases their cost 5–10 times, which results in lowering of their compatibility compared to aluminium alloys of other alloying systems, widely used in aviation. Considering the deficit and high cost of Al–Sc master alloy, it is recommended to dope the aluminium alloys by small additives of scandium together with zirconium in equal quantities, in order to save deficit scandium and improve their properties [19]. Doping of aluminium-lithium alloys by scandium should be performed with caution, considering that this additive promotes the alloy embrittlement and lowering of fracture resistance characteristics.

Among the disadvantages it should be noted that the extravagant alloying elements of this alloy series make them unsuitable for processing into other alloys. The high cost of lithium makes it necessary to process lithium-containing alloys only from their wastes [20]. Application of lithium alloys is complicated by many production and metallurgical factors. At plastic deformation, formation and development of shear bands occurs, and their transformation into cracks is possible, which eventually causes fracture. Fracture along the shear bands is a feature of aluminium-lithium alloys [21].

When defining the area of Al–Li alloy application, it is necessary to take into account the data on solid solution stability and baking. The most widespread error is application of an alloy with low solid solution stability for manufacturing thick-walled semi-finished products, for instance complex-shaped stampings. In this case, “dark spots” appear on the massive element surface, and zones of incomplete quenching form in the central part, which lower the characteristics of static and cyclic crack resistance.

DISCUSSION OF PROBLEMS IN THE FIELD OF ALUMINIUM ALLOY WELDING

Introduction of welding technologies is one of the most highly productive and cost-effective methods of making permanent joints, which allows fabrication of structural elements of the most rational shape and dimensions, making them maintainable. Let us consider the current problems in welding aluminium alloy structures. The constraints for application of the considered aluminium alloys in welded joints are as follows:

- considerable softening (up to 50 %) under the impact of the thermal cycle of fusion welding;
- low hot cracking resistance;
- lower values of ductility and fracture toughness in the direction of the height;
- multistep procedure of manufacturing the semi-finished products and/or finished products;
- need for alloying the filler materials by deficit and expensive master alloys to form welds with higher values of hot cracking resistance, as well as mechanical properties (particularly, LCF) of welded joints;
- and tendency to embrittlement developing at a high degree of deformation.

The following technological solutions are used to prevent cracking or other defects in the welds during welding of the alloys:

- producing such a structure, which enables a significant grain refinement (in particular, with application of electron beam technologies);
- limiting penetration of harmful impurities such as hydrogen (H) into the weld;
- regulation of the crystallization process at application of welding processes, characterized by minimal energy input;
- weld alloying.

The common regularity of all the aluminium alloys is formation of a softening zone, the size of which depends on the alloy type, its chemical composition and welding heat input. When producing a welded joint with the required parameters of weld depth and width, usually the requirement of minimizing the HAZ is also made, in order to ensure minimal deterioration of the physicomechanical properties as a result of recrystallization [22]. At heating in welding, a wide range of structural and phase transformations usually take place, including further decomposition of the solid solution and its repeated formation. It leads to different HAZ subzones being in the state of recovery, artificial aging, partial annealing and repeated quenching. The welded joint properties, as well as the possibility of strengthening at repeated artificial aging and the level of properties relative to the initial state, respectively, depend on the extent of development of this or that process [23].

Metallographic studies show that fracture of the metal of the weld and near-weld zones occurs as a result of the change in the initial structure of the semi-finished products. Such changes are less pronounced at EBW and, possibly, in laser welding, which ensures a higher level of the studied characteristics of welded joints. The advantages of electron beam process of aluminium alloy welding include the possibility of making a metallurgical impact on the weld pool with minimal weld alloying. Due to that, the welded joints turn out to be close to the base metal by their thermophysical properties. The weld structure is characterized by 4–5 times finer grain compared to base metal, and this is exactly the main difference between them. In addition to the fine equiaxed grain structure, a homogeneous distribution of copper in the matrix is also observed. A high density and dispersity of excess phases is also found, which is due to high rates of weld metal crystallization. Increase of the degree of deformation prior to quenching leads to reduction of the dimensions of recrystallized grains forming as a result of subsequent quenching, which ensures high mechanical properties.

In welding the process of formation of a weld of a homogeneous composition is important, which provides the high quality of welded joints, required mechanical properties and minimal residual stresses. To ensure the correspondence of the characteristics of the material being welded and the weld metal, it is most often recommended to use filler material of the same composition, as the base metal, or close to it. For alloys of Al–Cu–Li system such an approach is not rational, because of the low resistance to hot cracking. Therefore, for this class of alloys FSUE "VIAM" developed filler materials based on an alloy of Al–Cu system with additives of effective modifiers, including those with rare-earth metals (REM) [24]. Investigations with optimization of the quantity of modifiers, added to the alloy, are conducted under the conditions of commercial production, where the ingot crystallization rates are low and they are furtheron subjected to pressure treatment (pressing, extrusion, rolling). In the case of weld metal the situation is somewhat different. The weld has a cast structure which is not subjected to further pressure treatment, and melt crystallization rates are by 1–2 orders of magnitude higher than in commercial production of the alloys. In work [25] it is reported that application of high energy density sources, such as the electron beam, will allow optimizing the quantity of modifiers (scandium) added to the alloy. It is stated that in this case increase of mechanical properties of the metal of welds will be due to grain refinement and solid solution strengthening of the cast metal.

Porosity in EB welded joints in a number of cases can be a serious obstacle for effective application of this welding process in industry. The main cause for porosity is believed to be a jumplike lowering of hydrogen solubility in the weld metal at solidification (crystallization). Appearance of such porosity usually is the consequence of a severe violation of optimal welding conditions, including preparation of base metal and welding wires, as well as high content of gases in the metal being welded. Elimination of such porosity is complicated even at multiple remelting of the weld.

Much less difficulties arise during welding with subsequent strengthening heat treatment, which ensures equal strength of the welded joint metal and base metal. Alloy welding can be performed in the hot-deformed state or after quenching with performance of repeated thermal-strengthening treatment. Here, the welded joint strength is increased, but its ductility is decreased.

The advantages of this process compared to arc welding are especially noticeable at EBW of heat-hardenable aluminium alloys. Producing tight welds is largely ensured when alloying the weld pool by elements lowering the gas solubility in the liquid metal or binding them into stable compounds. Here, alloying element addition to the weld pool is performed by different methods: through filler wire fed under the electron beam during welding, or through metal foil or plates, which are preliminarily inserted into the butt, as well as spraying alloying elements on the edges being welded, or deposition of a metal-organic compound [26].

It is characteristic that due to a combination of high specific strength and specific modulus of elasticity, the aluminium-lithium alloys, while ensuring production of strong welds, usually do not meet the requirements to equal strength of welded joints. It is known that the strength coefficient of such materials after argon-arc welding is usually equal to 0.5–0.65 % of tensile strength of the base material. Equal strength of the base metal and welded joint can be achieved through reinforcement of the welding zones, or additional work hardening. To compensate for the loss of strength and ensure equal strength of the welded joints and base metal the butt joint is located in a region of thicker welded edges. Thickening is usually equal up to 100 % of the thickness of the welded metal, and the width of the thicker region should always be greater than that of the HAZ. It means a significant increase of welded structure weight. Now the EBW joints have tensile strength 15–25 % higher, and HAZ width 2–3 times smaller than with the arc methods. It allows greatly reducing the weight characteristics of welded structures. Welding aluminium alloys by the electron beam can be performed in the unsupported position and in different positions in space without application of substrate or forming devices, as the weld pool has a small volume of liquid metal due to a high heat conductivity of these alloys. It is important in welding structures, requiring a guaranteed penetration of the butt through its entire thickness in the absence of access to the butt joint reverse side. The impact toughness of the metal of the weld on aluminium alloys is always higher than that of the base metal, and the proof strength practically remains on the level of these properties of the base metal. With increase of the number of passes, the tensile strength decreases by 10–30 MPa, irrespective of the initial state of the material before welding, even on annealed material [12].

The influence of initial tempering before welding and postweld treatment on the strength and elongation of welded joints also depends on their thickness [27–30]. Both base metal and weld strength increase with reduction of elongation. Fracture runs in the weld HAZ prior to any significant elongation occurring in the base metal.

To sum up, we can note that three main kinds of heat treatment became widely accepted for aluminium alloys: annealing, quenching, thermomechanical treatment and aging as a means to improve the functional properties. Application of postweld heat treatment (quenching + artificial aging) ensures equalizing of the grain structure of the welded joint at recrystallization and change of the morphology of precipitates on the grain boundaries, which improves the strength of welded joints to 0.9 of base metal strength. Despite a certain lowering of ductility values, significant advantages of the new alloys as to rigidity and tensile strength are obvious. However, at application of lithium-containing alloys it was found that achievement of high strength properties of aluminium alloys most often is detrimental to their adaptability-to-manufacture.

Furtheron, development and introduction of alloys, having significantly higher strength characteristics at preservation of adaptability-to-manufacture, will allow even further improvement of the reliability and residual life of structures, and lowering of their weight and metal intensity.

Thus, fabrication of high-tech welded structures from aluminium alloys involves two interconnected directions of investigations: creation of new high-tech alloys, as well as development of different technological processes of joining them with application of modern welding technologies that, eventually, determines the possibility of creation of advanced aerospace products.

CONCLUSIONS

1. On the whole, weldable aluminium alloys remain to be the main structural materials for aerospace industry. Their application ensures higher weight effectiveness, and an increase of the structure strength and reliability at a significant weight reduction. On the other hand, increase of the abovementioned characteristics is based on a complication of the chemical composition, heat treatment modes and other technological measures, leading to lowering of the material ductility properties.

2. Results of the conducted literature review indicate that at present materials scientists have created original compositions of complex aluminium alloys of different alloying systems with microadditives of effective modifiers of REM type, which feature higher characteristics of adaptability-to-manufacture and strength.

3. Despite a range of technological difficulties, third generation alloys of Al–Mg–Li–Zr and Al–Cu–Li–Zr systems are promising materials in aircraft construction. However, despite the high adaptability-to-manufacture of aluminium-lithium alloys at application in the aerospace industry, we should not forget about the high toxicity of welding these alloys for humans.

4. Allowing for all the mentioned factors in their totality ensures achievement of not only higher level of heat resistance and strength of the alloys, their anisotropy, but also their good adaptability-to-manufacture. In manufacture of cryogenic welded products for flying vehicles, 2219 aluminium alloy remains the best choice at this moment among the dispersion-hardening alloys.

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ORCID

V.I. Zagornikov: 0000-0003-0456-173X

CORRESPONDING AUTHOR

V.I. Zagornikov
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: zagornikov@technobeam.com.ua

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