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Development of a New Aluminium-Lithium Alloy of Al-Cu-Mg-Li (Ag, Sc) System Intended for Manufacturing Sheets, Thin-Walled Sections and Forgings

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Aluminium-lithium alloys are known to uniquely combine the mechanical properties: low density, increased elastic modulus, and quite high strength properties which make it possible to use these alloys as aircraft structural material and to improve aircraft performance characteristics. At the same time aluminium-lithium alloys have a number of limitations – low ductility on the verge of maximum strength, low corrosion resistance, particularly when in form of thin-walled semi-finished products. A new aluminium-lithium alloy with increased ductility and corrosion resistance has been developed. It enables production of thin sheets, thin-walled sections and forgings maintaining the strength and performance characteristics required for structural aircraft materials.
Optimal chemical composition of the alloy provides a means for copper to become solid solution which significantly decreases volume ratio of gross intermetallic compounds of copper bearing phases and accordingly increases the alloy ductility. Additional alloying with alkaline-earth metals and limiting alkaline metals and gallium results in more favorable conditions for shear deformation and as a consequence increase of alloy ductility. Introduction of vanadium, scandium and zirconium contributes to homogeneous fine-grained structure which provides structural strengthening of semi-finished products and parts of the alloy and which makes it possible to achieve the required level of the alloy strength properties. Introduction of argentums contributes to more equal distribution of strengthening phases in solid solution and more equal precipitation of dispersoids during ageing. That results in increase of both strength and corrosion properties of the alloy.

Key Words: *Al-Li alloy, phase composition, sections, sheets, properties*

1. Introduction

It is known well [1], that aluminium-lithium alloys have unique combination of mechanical properties, i.e. low density, high elastic modulus, and rather high strength properties. The above-mentioned properties make it possible to use the alloys of this system as structural material for aerospace engineering to improve some aircraft performance characteristics including aircraft weight reduction, fuel economy, loadlifting capacity.

At the same time aluminium-lithium alloys have one drawback of low ductility, i.e. ability to sustain the amount of plastic deformation without fracture. Stable production of thin sheets (0.3 - 0.5 mm thick) without macro- and micro cracks cannot be achieved due to inadequate ductility of the present Al-Li-Cu-Mg system aluminium-lithium alloys, especially during cold rolling.

As a result of our efforts to search for the ways to increase processing ductility of Al-Li-Cu-Mg system alloys, we developed a new alloy through changing of alloying technique with zirconium, adjusting ingot homogenization parameters and changing alloy chemical composition [2]. We managed to manufacture sheets 0.3 mm thick of this alloy. But in the course of research it became apparent that the thinner the semi-finished product, the less its corrosion resistance. We continued the research.

2. Improving properties of Al-Li-Cu-Mg alloy through changing its chemical composition and additional alloying with silver

In the course of the study on aluminium alloy of 1441 grade the authors of the work found out that increased content of copper resulted in forming of coarse intermetallic compounds of irregular shape inside the grains and on the grain boundaries; there were copper-bearing phases that formed during alloy solidification in the areas of increased content of copper. Those phases were not separate particles but large aggregations that hindered shear deformation during working which led to significant reduction of alloy ductility.

Electron microscope investigation showed that copper reduction in the alloy down to 1.3 – 1.5 mass % enabled practically complete transformation of it into solid solution; that resulted in considerable reduction of volume ratio of coarse intermetallic compounds of copper-bearing phases and therefore in alloy ductility increase.

Introduction of silver into the alloy contributes to more equal distribution of strengthening phases in solid solution and more equal precipitation of dispersoids during ageing. That leads to increase of both strength and corrosion properties of the alloy.

It has been established that adding one or more elements of calcium, barium, bismuth group in amount of 0.0005 – 0.05 mass% and 0.0001 – 0.05 mass% correspondingly contributes to sodium stable phase [3], whereby alloy ductility increases and susceptibility to grain-boundary corrosion decreases.

After solution heat treatment and ageing copper, lithium and magnesium - the main alloying elements - form sufficient amount of strengthening elements (dispersoids) to obtain good balance of strength and plastic properties.

Zirconium and scandium provide equiaxial fine grain structure during casting, which contributes to good alloy processability both during casting and plastic working and improves alloy corrosion behavior.

On the basis of the theoretical research and experiments we propose a new alloy with the following balance of components, mass%: lithium - 1.6 – 1.9; copper- 1.3 – 1.5; magnesium – 0.7 – 1.1; zirconium – 0.04 – 0.2; beryllium – 0.02 – 0.2; titanium – 0.01 – 0.1; nickel – 0.01-0.15; manganese – 0.01 – 0.2; gallium – up to 0.001; zink – 0.01 – 0.3; sodium - up to 0.0005; calcium - 0.005 – 0.02; and at least one element of the group including vanadium - 0.005 – 0.01 and scandium - 0.005 – 0.01; aluminium – the rest.

We manufactured various semi-finished products of the alloy: sheets and plates, forgings, extrusions. Semis of the proposed alloy can be used for different applications, e.g. aircraft fuselage panels, frame elements, welded fuel tanks and other components for aerospace engineering.

In accordance with the proposed chemical composition we cast billets of 305 mm dia. and ingots of 300x1,100 mm. Billets and ingots were used for manufacturing of extrusion sections and sheets, correspondingly. The chemical composition of the cast ingots/billets is shown in Table 1 (1445 alloy). The chemical composition of the previously developed alloy (1141K) is specified in Table 1 for reference.

Table 1 Chemical composition of alloys

Alloy	Content of elements, %															
	Al	Si	Fe	Cu	Mn	Mg	Ti	Ni	Zr	Be	Li	Na	Zn	Sc	Ca	Ag	Ba
1445	Base	0.04	0.07	1.8	0.17	1.0	0.04	0.11	0.10	0.003	1.5	0.001	0.11	0.03	0.02	0.15	0.01
1441K	Base	0.03	0.15	1.4	0.056	1.0	0.03	0.04	0.11	0.03	1.8	0.001	-	-	-	-	-

3. Results and discussion

3.1. Investigation of phase composition of the new alloy

In the first place we conducted differential thermal analysis of the new as-cast alloy. It is established that the temperature of non-equilibrium solidus of the alloy is 532°C. This value was a basis for developing homogenization and solution heat treatment parameters of the new alloy.

The specimens sampled from cast and homogenized billets were investigated using an electron microscope with add-on device for X-ray spectrum analysis. The typical form of structural components of the alloy is given in Fig. 1. The results of quantitative X-ray spectrum microanalysis of the structural components presented on Fig. 1 are given in Table 2.

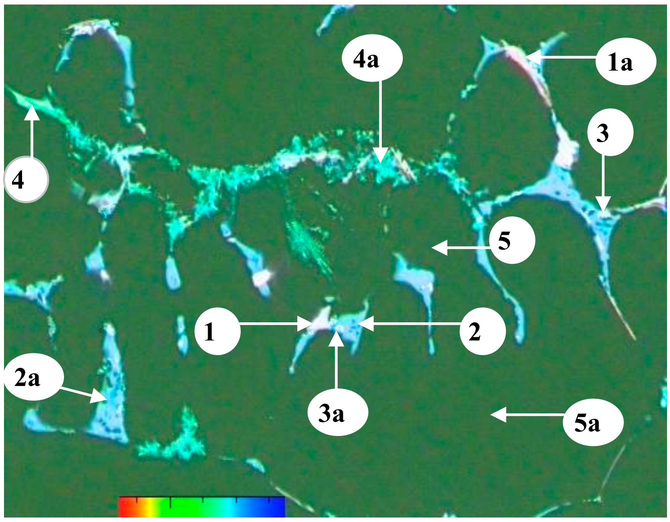


Fig.1 Structural components of Ø 305 mm billet, 1445 alloy, homogenized (500°C, 24 h)

Table 2 Results of quantitative X-ray spectrum microanalysis of structural components of Ø 305 mm billet, 1445 alloy

Point	Content of elements, mass %											
	Al	Mg	Si	Ca	Sc	Mn	Fe	Ni	Cu	Zn	Zr	Ag	Li*
1	63.12	1.50	0.20	3.81	0.09	0.49	1.47	2.87	26.54	0.24	-	0.10	-
1a	47.36	-	9.38	11.30	0.66	-	0.35	4.64	24.72	0.17	0.45	-	0.97
2	49.27	10.81	0.88	-	0.12	-	0.11	0.12	36.13	0.65	0.12	1.8	-
2a	48.96	10.88	1.00	-	0.15	-	-	0.16	35.80	0.59	-	2.57	-
3	50.32	2.77	0.25	0.14	-	-	0.37	16.47	28.18	0.34	-	0.23	-
3a	55.51	3.67	0.37	-	-	-	1.41	12.65	24.79	0.22	-	0.61	0.93
4	65.16	0.43	-	-	-	2.79	17.75	5.98	6.83	-	-	0.53	0.53
4a	66.69	2.31	0.37	0.11	-	0.80	8.28	8.86	10.49	-	-	0.62	1.47
5	95.11	1.04				0.13	-	-	1.58	-	0.16	0.17	1.81
5a	95.47	1.13	-	-	-	0.14	-	-	1.88	0.16	0.16	-	1.06

The structural components are present in the alloy mainly in the form of disperse particles of various shape (irregular, needle-shaped, thin plate-like, rounded). The mix of highly dispersed particles makes it impossible to determine the exact composition of individual particles. As a result, the composition of the particles is determined rather qualitatively: low-temperature eutectic contains Al(CuMgLi) compound (points 3a, 4 and 4a); insoluble compounds are Alx(Cu,Ni,Ca) particles (point3); Alx(Cu,Ni,Fe) (point 3a); Alx(Zr,Sc) (points 1a and 2). There are also Al_2CuLi phase (point 2) and AlCuMg(Ag) phase (points 2 and 2a). Scandium usually is a constituent of copper-bearing phases. Solid solution composition (points 5 and 5a) after homogenization conforms to optimal chemical composition of the alloy.

3.2. Selection of heat treatment parameters of the new alloy

Three types of sections of the new alloy from 8 mm thick (Fig. 2a) to 1.5 mm thick (Fig. 2b) were extruded.

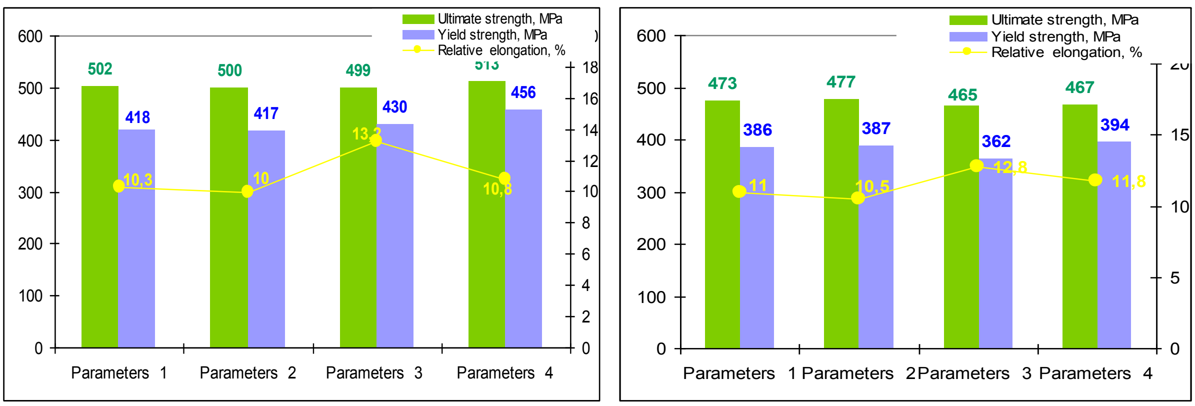
a) b)

Fig.2 Cross-section of 1445 alloy sections:
a) wall thickness is 8 mm; b) wall thickness is 1.5 mm;

To choose heat treatment parameters the specimens sampled from hot-extruded sections in laboratory conditions were heat treated under the following conditions:

1. Quenching from temperature of 525 – 535°C, 25 minutes of soaking, correction with 1.5% residual stress (the interval between quenching and correction being up to 2 hours); ageing at 145 – 155°C, 30 hours of soaking;
2. Quenching from temperature of 525 – 535°C, 25 minutes of soaking, correction with 1.5% residual stress (the interval between quenching and correction being up to 2 hours); ageing at 145 – 155°C, 36 hours of soaking;
3. Quenching from temperature of 525 – 535°C, 25 minutes of soaking, correction with 1.5% residual stress (the interval between quenching and correction being up to 2 hours); ageing at T_I = 145 – 155°C, 4 hours of soaking + T_{II} = 165 – 175°C ; 24 hour of soaking;
4. Quenching from temperature of 525 – 535°C, 25 minutes of soaking, correction with 1.5% residual stress (the interval between quenching and correction being up to 2 hours); ageing at T_I = 145 – 155°C, 4 hours of soaking + T_{II} = 165 – 175°C ; 34 hour of soaking.

Mechanical properties of the sections versus heat treatment parameters are given in Fig. 4.



a) b)

Fig. 4 Mechanical properties of 1445 alloy sections with 8 mm (a) and 1.5 mm (b) wall thickness

3.3. Investigation of mechanical and corrosion properties of sheets

Uncladded sheets were manufactured of 1445 and 1441K alloys. Sheets 6.5 mm thick were rolled in a coil at 440-450°C.

Cold rolling was performed on the following reduction pass schedule: 6.5 mm - 5.0 mm - 4.0 mm - 3.6 mm - 2.9 mm - 2.0 mm - 1.4 mm. Coils have been produced with sheet sizes: 0.6 x1,200 x4,000 mm.

The sheets were solution heat treated and aged under conditions No. 4. The mechanical properties of the sheets are given in Table 3.

Table 3 Mechanical properties of sheets

Alloy	Sampling direction	Sheet size, mm	Mechanical properties		
			TS, MPa	YTS, MPa	A_{50}, %
1441K	longitudinal	0.6x1,200x4,000	430-435	335-350	11 - 15
	transverse	0.6x1,200x4,000	420-455	330-370	10 - 14
1445	longitudinal	0.6x1,200x4,000	450-465	385-400	11 - 16
	transverse	0.6x1,200x4,000	435-455	350-375	14 - 22

We determined corrosion characteristics of the sheets 2.4 mm thick of 1441 and 1445 alloys heat treated under the following laboratory conditions: quenching at 528+2°C, 30 minutes of soaking; ageing at 160+2°C, 30 hours of soaking.

As for general corrosion, 1441 alloy sheets are given 7 grades, classed as IV group of resistance and described as relatively resistant, 1445 alloy sheets are given 6 grades, classed as IV group of resistance and described as relatively resistant.

As for layer corrosion, 1441 alloy sheets are given 4 grades, classed as III group of resistance and described as resistant, 1445 alloy sheets are given 5 grades, classed as III group of resistance and described as resistant.

As for intergranular corrosion, 1441 alloy sheets are given 5 grades, classed as III group of resistance and described as resistant, 1445 alloy sheets are given 4 grades, classed as III group of resistance and described as resistant.

The specimens of 1445 alloy sheets displayed the best corrosion characteristics. The results of corrosion investigations are given in Table 4. The view of the sheets after general corrosion test is presented in Fig. 4.

Table 4 Results of general corrosion, layer corrosion and grain-boundary corrosion tests of sheets 2.4 mm thick

Alloy	General corrosion				Layer corrosion		Intergranular corrosion			
	gr/m^2h	mm/year	Grade	Resistance group	Grade	Resistance group	Penetration, mm	Spread, %	Grade	Resistance group
1441	0.256	0.869	7	IV	4	III	0.244	50	5	III
1445	0.081	0.275	6	IV	5	III	0.144	50	4	III

a)
b)

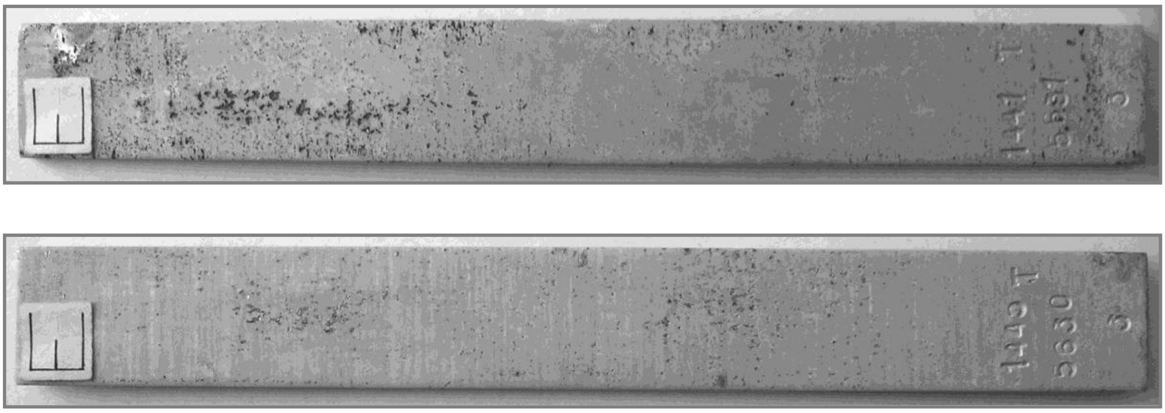


Fig.4 Typical view of specimens of 2.4 mm thick sheets of 1441 and 1445 alloys after general corrosion test and corrosion products removal:
a) 1441 alloy specimen; b) 1445 alloy specimen

4. Summary

We have developed a new aluminium-lithium alloy of Al-Cu-Mg-Li system with increased ductility which enables production of thin sheets down to 0.3 mm thick, thin-walled sections and forgings maintaining the strength and performance characteristics required for structural materials for aircraft engineering.

Taking the research results as a basis, the authors proposed the optimal chemical composition of the alloy. Volume ratio of coarse intermetallic compounds of copper-bearing phases can be significantly reduced by means of practically complete transformation of copper into solid solution; therefore alloy ductility can be increased.

Additional alloying of the alloy with alkali-earth metals creates good environment for shear deformation and results in alloy ductility increase. Introduction of silver, scandium and zirconium contributes to homogeneous fine-grained structure which provides structural strengthening of semi-finished products and parts of the alloy and makes it possible to achieve the required level of the alloy strength properties and at the same time to increase corrosion resistance.

In summary, the proposed new alloy of Al-Cu-Mg-Li system provides achievement of an objective, i.e. increase of alloy ductility, processability, yield ratio when manufacturing semi-fnished products and parts of it. The new alloy opens up possibilities of manufacturing of thin sheets, thin-walled sections and forgings providing decreasing of labor-output ratio and maintenance of the strength and performance characteristics of the alloy as well as semi-finished products and parts required for structural material of saircraft engineering.

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