

Structure and Mechanical Properties of Al-Li Alloys as Cast

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Abstract

The high mechanical properties of the Al-Li-X alloys contribute to their increasingly broad application in aeronautics, as an alternative for the aluminium alloys, which have been used so far. The aluminium-lithium alloys have a lower specific gravity, a higher nucleation and crack spread resistance, a higher Young's module and they characterize in a high crack resistance at lower temperatures. The aim of the research planned in this work was to design an aluminium alloy with a content of lithium and other alloy elements. The research included the creation of a laboratorial melt, the microstructure analysis with the use of light microscopy, the application of X-ray methods to identify the phases existing in the alloy, and the microhardness test.

Keywords: Al-Li alloys, Aerospace industry, Precipitation hardening

1. Introduction

The development of aluminium-lithium alloys started from a Li addition to aluminium-copper, aluminium-manganese and aluminium-copper-magnesium alloys [1]. The aluminium alloys whose main element is lithium do not fall into a separate group; they belong to the 8xxx, 2xxx and 5xxx series. It has been assumed that if, in the marking of the series, the third digit is 9, then lithium is the alloy element, e.g. 8090, 2090, 2099. Lithium has the lowest density among metals, which equals 0,54 g/cm³ (much lower than aluminium) and thus each 1% of the lithium addition lowers the alloy's density by 3% and increases the Young's module by 6%. The mechanical properties of the high-strength Al-Li alloys, as compared to those of the conventional ones, can be increased by a few percent. An important property of Al-Li alloys is their high corrosion

(also stress) resistance. What is more, lithium has an especially good effect on the improvement of the fatigue resistance, the crack resistance as well as the impact resistance at low temperatures. Lithium has a high solubility in aluminium reaching up to about 14% at 600°C, which decreases together with temperature, and this creates a possibility to model the mechanical properties using of heat treatment [2, 3]. In the Al-Li phase equilibrium system (Fig. 1) the following phases are present: a solution of Li in Al, α , with the RSC structure, an intermetallic phase, δ , based on the AlLi compound with a variable solubility in Li in the range from about 45 to 55% at; intermetallic compounds: Al₄Li₃, stable up to 520°C, and Al₄Li₉, stable up to 330°C [4].

The condition enabling the dispersion hardening of the metal alloys is the drop of the alloy element's solubility in the solid solution together with the temperature decrease. The

strength increase of the aluminium-lithium alloys after the heat treatment is a result of the intermetallic phase precipitation in the solid solution [5, 6]. The mechanical properties of the alloy are significantly influenced by the presence of metastable phases, which are formed under non-equilibrium conditions. Figure 2 presents the curve of the solubility limit of Li in Al. Within the range of low contents of lithium, the only equilibrium phase, beside the solid solution α , is the intermetallic phase δ .

The reinforcing factor in these alloys is the metastable phase δ' (Al_3Li) with the RSC structure, which precipitates during ageing. This phase has a small misfit with the matrix [6].

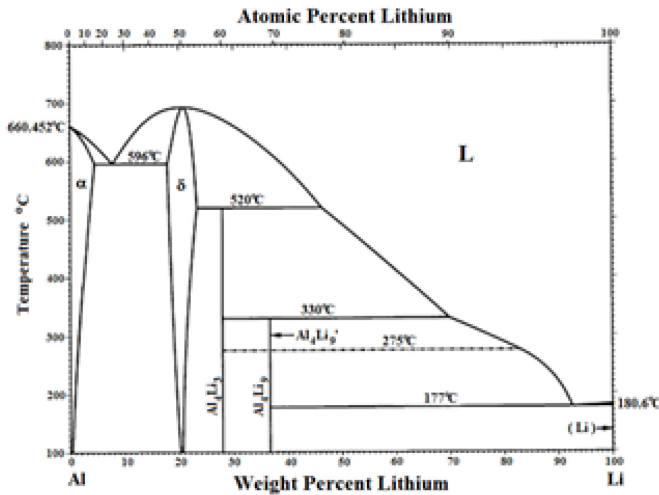


Fig. 1. Phase equilibrium diagram of Al-Li [4]

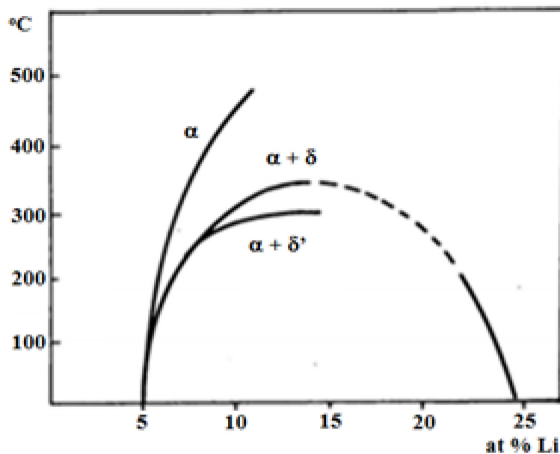


Fig. 2. A section of a phase diagram with the position of the solubility limit's line α [6]

In Al-Li alloys, the alloy additions mainly applied are copper, magnesium and zirconium, with the aim to improve the ductility, the grain refinement and the crack resistance. Due to the high production costs (the costly melting and casting technology), some criteria have been established which an alloy must meet in order to be economically useful. And so, the requirements include the density to be lower by at least 10% and the Young's module to be higher by 10÷15%, as compared to the traditional alloys [2]. The nominal composition of some aeronautic Al-Li-X alloys is shown in Table 1.

Table 1.

Nominal composition of selected aeronautic Al-Li-X alloys [7]

Alloy marking	Content % wt.				
	Cu	Li	Mg	Zr	Other
2020	4.5	1.3	-	-	Mn 0.5 Cd 0.25
2090	2.7	2.2	-	0.12	-
2091	2.1	2.0	1.5	0.10	-
8090	1.3	2.4	0.9	0.10	-
8091	1.9	2.6	0.9	0.12	-
8092	0.65	2.4	1.5	0.12	-
1420	-	2.0	5.0	0.12	Mn 0.5
2297	2.8	1.5	-	0.12	Mn 0.3
2195	4.0	1.0	0.5	0.12	-

Aluminium-lithium alloys are the most often reinforced by a combination of two types of reinforcements: grain refinement and precipitation [5].

The precipitated reinforcement is obtained by artificial ageing which involves hard dispersion secondary precipitation in the matrix. The effect of the ageing parameters (temperature and time) on the hardness of the Al+Cu and Al+Cu+In alloys are presented in Figure 3.

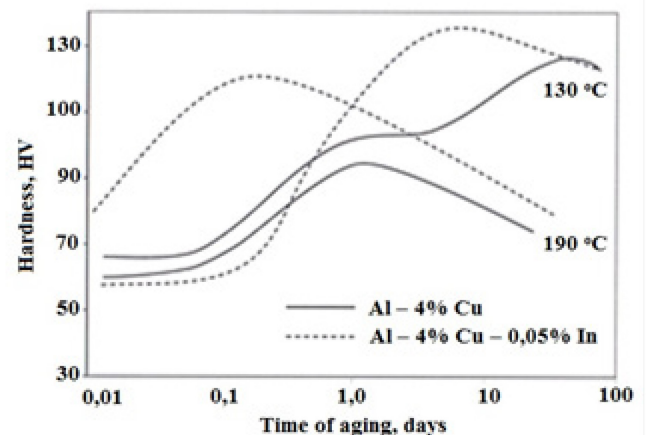


Fig. 3. Dependence of the HV hardness on the ageing time of Al-4Cu and Al-4Cu-0,05In alloys aged at 130 °C and 190 °C [2]

The properties of the high-strength Al-Li-X alloys depend on the microstructure, mainly on the size and morphology of the grains, the properties of the precipitate-free zones and the occurrence of texture. The microstructure characteristics which significantly affect the mechanical properties of the alloy are: the type and size of the precipitates, their distribution in the matrix as well as their coherence with the matrix [5, 6].

The phenomenon which adversely influences the mechanical properties of the alloy is the occurrence of precipitate-free zones at the grain boundaries. In the Al-Li-X alloys, as a result of the precipitation of phase δ' (Al_3X), at the grain boundaries, precipitate-free zones can occur.

These areas have a low crack resistance and contribute to the formation of cracks at the grain boundaries.

The consequence of this is a drop in the stress and fatigue corrosion resistance. High temperature and prolonged ageing can cause an increase of the precipitate size.

The precipitates at the grain boundaries stimulate an impoverishment of the boundary areas in the alloy elements [7].

The technology of producing Al-Li-X alloys consists of the following consecutive processes: the creation of an ingot, homogenization, cold or hot plastic treatment, oversaturation (with or without natural ageing) and artificial ageing. The Al-Li alloys characterize in a fine grain structure. Beside the usual reinforcing effects, the high grain refinement increases the number of barriers for the dislocation movement, which affects the improvement of the tensile strength and the crack resistance of the alloys. The size of the grain and the morphology depend on the parameters of the heat-plastic treatment. At high temperatures and low deformation rates, a dynamic recrystallization can also be observed [5]. The heat-plastic treatment can be used to influence the improvement of such alloy's properties as: impact resistance, plasticity, fatigue resistance, stress and layer corrosion resistance, by way of controlling the microstructure and precipitation processes [8].

In order to increase the fatigue resistance, the Al-Li-X alloys are enriched with such elements as Cu, Mg, Zr and Ag.

The Cu alloy addition dissolves in aluminium (up to certain content) and ensures a higher strength of the alloy, yet it also decreases the corrosion resistance. Adding magnesium to the alloy causes an additional increase of the material's strength. A lithium and silver content creates a possibility of precipitated reinforcement. A silver addition significantly influences the kinetics of the phase transformations [3]. In almost all types of Al-Li-X alloys, a zirconium addition is applied in the amount of 0,10-0,12%. Zirconium, beside its effect on the course of crystallization and the grain refinement, also facilitates the nucleation of phase δ . The Al_3Zr precipitates also contribute to the homogenization of the dislocation structure which is formed during the deformation. Copper and magnesium create additional precipitates in the boundary areas, which reduces the adverse tendency for the occurrence of precipitate-free zones [6, 9].

The aim of the research was a preliminary characteristic of the microstructure and mechanical properties of the model Al-4Cu-1Mg-1Li alloy. The work involved observations of the microstructure by means of light microscopy. A quantitative grain analysis, microhardness measurements and X-ray examinations were also performed, together with a qualitative phase analysis.

2. Test methodology

A model aluminium-lithium alloy was produced with additions of Cu, Mg, Ag and Zr. The results of the alloy's chemical composition analysis are presented in Table 2. It corresponded to that of the alloy marked with the symbol 2195.

The introduced alloy additions - Cu, Mg, Ag, Zr – were aimed at the improvement of the mechanical properties of the alloy after the heat treatment.

The produced ingot was shaped as a cylinder with the diameter of 17 mm and the height of 90 mm. The macroscopic image of the ingot is shown in Fig.4.

The examinations were performed on samples in the initial state (without heat treatment).

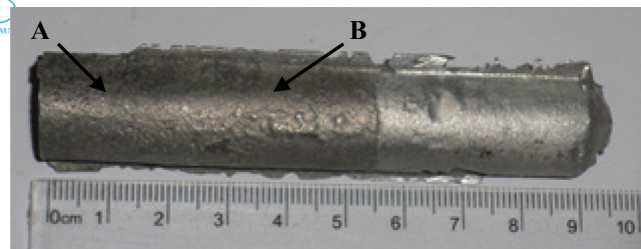


Fig.4. Image of the test alloy ingot with marked areas of microstructure and hardness tests

Table 2.

Chemical composition of alloy Al-4Cu-1Mg-1Li (alloy 2195), % wt.

Cu	Mg	Zr	Ag	Be	Li	Al
4,0	1,0	0,12	0,35	0,03	1,0	rest

The metallographic tests were conducted on samples which were cut out mechanically in areas A and B of the ingot, and next they were electrolytically ground and polished with the use of the LectroPol-5 device. For the polishing process, a reagent by Struers A2 was used. With the aim of revealing the microstructure, the tested material underwent chemical etching, with the application of Keller's reagent.

The following tests were performed:

- Microscopic observations by means of a LEICA DM 4000 light microscope.
- Quantitative grain size analysis of the matrix – a measurement of the chords' length with the application of the computer program SigmaScan Pro. The measurements were conducted on randomly generated secants on the recorded microstructure images, which intersected about 200 grains in areas A and B, marked in Fig. 4.
- Microhardness tests performed on samples from areas A and B by the Vickers method, with the use of a hardness tester by Innovatest, (load 100 G). The number of tests was 10. The calculations included the mean hardness values, the standard deviations and the measuring errors for the trust level $1-\alpha=0,95$ [10].
- X-ray diffraction phase analysis performed with the use of a diffractometer D500 by Siemens with monochromatic radiation of the lamp with a copper anode ($\lambda_{K\alpha Cu}=1,54 \text{ \AA}$).

Test conditions:

- angle step $\Delta 2\theta=0,02^\circ$
- counting time $\tau=5\div 10 \text{ s}$
- angle measuring range $2\theta=30\div 100^\circ$

3. Test results and analysis

The microstructure of the tested alloy was observed by means of a light microscope with the magnifications 100x, 200x and 500x. Exemplary microstructure images are presented in Figures 5 and 6.

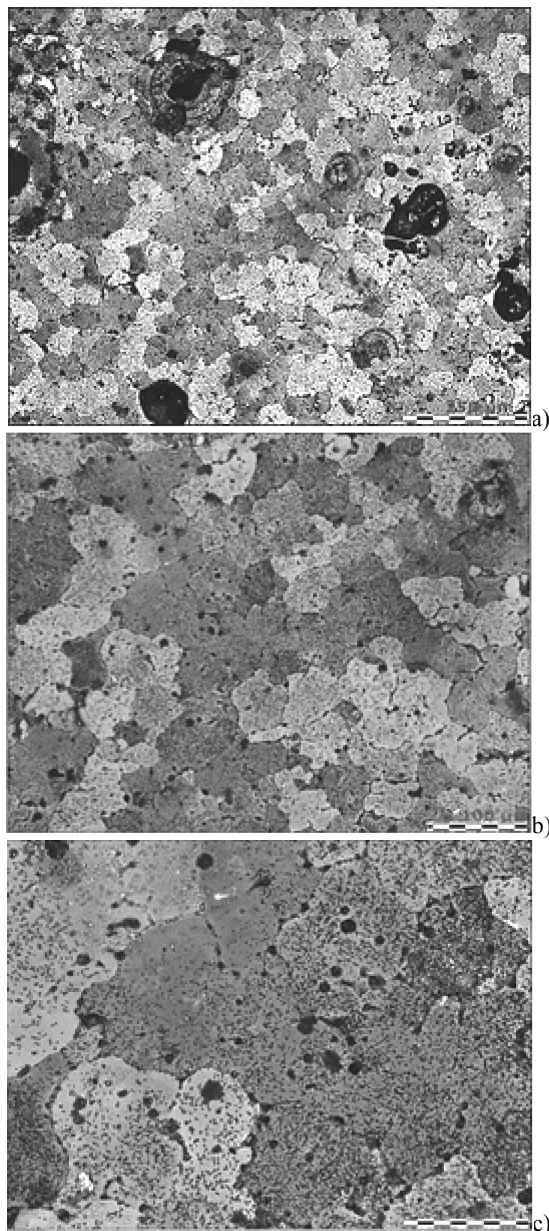


Fig. 5. Microstructure of alloy Al-4Cu-1Mg-1Li (alloy 2195), area A, magnifications: a) 100x, b) 200x, c) 500x

In the presented microstructure photographs, one can see the grains of phase α and fine-dispersive precipitates of intermetallic phases. Most of the precipitates are distributed inside the grains. In some areas, the distribution of the intermetallic phases is at the grain boundaries. They are larger in size than those inside the grains, although one can observe sporadic larger precipitates inside the grains as well. The grains have irregular shape but in general are equiaxial and microstructure is isometric. At the grains boundaries, there are probably low-melting phases rich in Mg. The identification of the precipitates requires the application of light microscopy.

The grain size analysis in areas A and B of the tested ingot showed that in area A, the mean grain chord length was 36,95 μm , whereas in area B, this value was 55,32 μm . Fig. 7 presents the empiric distributions of the matrix's grain chord lengths. It can be seen that the distribution of the grain chord lengths in area B is shifted to the right compared to the one in area A.

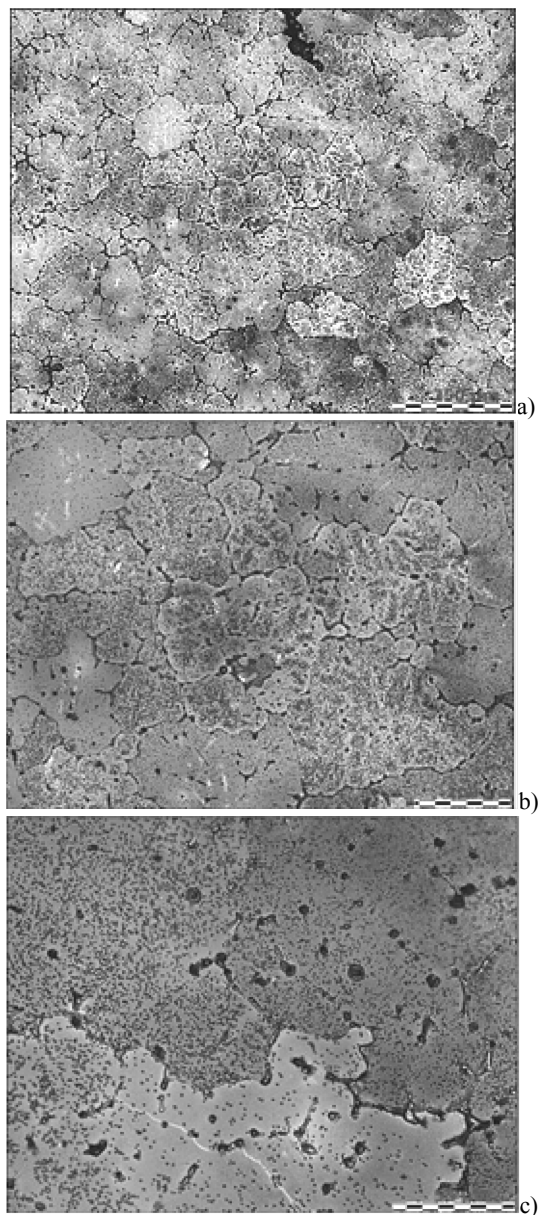


Fig. 6. Microstructure of alloy Al-4Cu-1Mg-1Li (alloy 2195), area B, magnifications: a) 100x, b) 200x, c) 500x

The results of the microhardness measurements are presented in Table 3. No difference was stated between the microhardness values in areas A and B, and so Table 3 includes only area A's measurement results

The mean microhardness of the tested alloy was $128 \pm 1,7 \text{ HV}_{0,1}$. The standard deviation was 2,21.

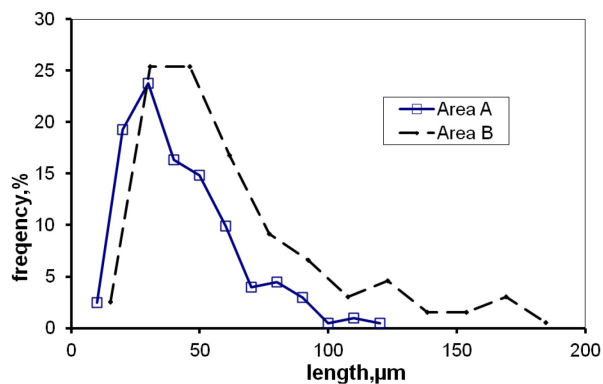


Fig. 7. Distributions of the matrix's grain chord lengths in areas A and B of the tested ingot

Table 3.

Microhardness test results for alloy Al-4Cu-1Mg-1Li (alloy 2195) with calculated mean \bar{x} and standard deviation $s(x)$ values

Test No.	HV
1	125,8
2	127,8
3	124,4
4	127
5	129,7
6	129
7	131,9
8	130,2
9	127,1
10	127,3
\bar{x}	128,02
$s(x)$	2,21

The X-ray qualitative phase analysis performed on the Al-Li alloy showed a content of only phase α (Fig. 8). This results from the low contents of the alloy elements. The highest mass fraction belongs to aluminium (93,32%). The peaks visible in the diagram come exclusively from phase α Al, which crystallizes in lattice Al (RSC). Above the peaks, the families of the planes from which the peaks come from have been marked. The specificity of the test made it impossible to measure the phases and elements below the content of 5% and thus the diagram shows only α phase.

4. Test result discussion

The modern Al-Li-X alloys have found their application in the new generation aeronautic constructions, replacing the high-strength aluminium alloys which have been used so far. These alloys characterize in high strength; however, the good strength parameters are accompanied by a low ductility, which makes a practical application of the binary Al-Li alloys impossible. The reasons for such a low ductility of binary alloys are the following [3]:

- the localization of the plastic deformation as a result of particle shearing δ^* ,

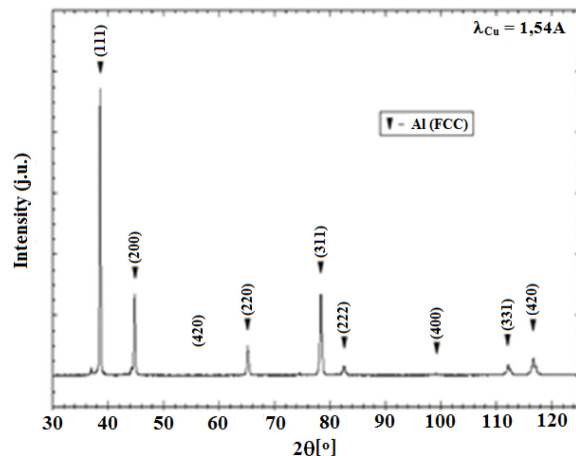


Fig. 8. Diffraction record of qualitative phase analysis of alloy Al-4Cu-1Mg-1Li (alloy 2195)

- the localization of the plastic deformation in the precipitate-free areas,
- the presence of equilibrium phase precipitates at the grain boundaries.

The flaws of these alloys are, among others, a significant drop of plasticity and ductility during ageing up to the maximal strength. This adverse phenomenon can be minimized by way of heat-plastic treatment [11].

Additions of such alloy elements as Cu, Mg, Zr or Ag simultaneously increase the strength and ductility of the tested alloy. What is more, they cause an increase in the specific gravity of the alloy. A proper heat-plastic treatment allows for wide-range changes in the mechanical properties of the examined alloys. It is worthy to emphasize, that Li increases corrosion resistance of ultralight Mg-Li alloys [12].

The investigations discussed in this work constitute the first stage of the research on the Al-Li-X alloy, marked with the symbol 2195.

The microstructure observations revealed the presence of high density precipitates of intermetallic phases, both inside the grains and at the grain boundaries.

Large particles of intermetallic phases do not have any significant effect on the yield point and the ultimate tensile strength. They can, however, cause a significant drop in the ductility and the crack resistance. These particles crack already with a small plastic deformation. Voids are formed around them, which join together during further deformation, forming cracks, which lead to premature ageing of the material. Another reason for the void formation under tensile stress can be the separation of the matrix from the particles, caused by the lower cohesion at the interface. One of the reinforcing phases in these alloys is the metastable, ordered intermetallic phase δ' (Al_3Li), which is coherent with the matrix and demonstrates especially high agreement of the crystalline structure parameters and those of the matrix. That is why the particles of this phase remain coherent with the matrix even after long-term ageing which causes their coagulation. The nucleation of phase δ' is homogeneous in the whole volume of the alloy. Due to the similarity of the crystalline structure and the atomic radii of aluminium and lithium, the precipitates of this phase have a spherical shape. [2].

The preliminary analysis of the matrix's grain size revealed a diversity of the grain size on the length of the tested ingot. Smaller grains were observed in area A, for which the mean grain chord length was 36,95 μm , whereas in area B (ingot's centre), this value equaled 55,32 μm .

The mean hardness of the tested alloy in the initial state was 128 HV. It should be noted that this hardness is higher than that of the Al-Cu alloys after the heat treatment (Fig. 3).

Alloy 2195 belongs to the group of modern high-strength aluminium alloys, applied in the aerospace industry. It characterizes in high fatigue resistance, and its crack resistance, assessed on the basis of the K_{IC} test, increases with a temperature drop. This alloy demonstrates super-plastic properties. The next research stage is planned to include an analysis of the effect of heat-plastic treatment on the microstructure (type and dispersion of intermetallic phases) and the mechanical properties of the alloy.

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