A STUDY OF PHASE COMPOSITION AND PLASTICITY OF ANNEALED Al-Li-Cu-Mg-Zr ALLOYS

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Introduction

The annealed Al-Li alloys containing more than 1.5 wt.% of Li show the low plasticity during cold working. It makes difficulties for cold coil rolling where the coil annealing is followed by slow cooling [1,2]. The main cause of low plasticicity for annealed Al-Li alloys is the high volume fraction of brittle equilibrium phases. It is higher than that of the conventional commercial aluminum alloys because of low Li atomic and specific weight [2]. From these facts it transpires that Al-Li alloys plasticity during cold deformation is firstly determined by Li content. The effect of other components concentration, introducing into the commercial Al-Li alloys compositions, on the plasticity wasn't studied. Mg content is of great interest as far as its increase in the alloys of 5000 series significantly improves their mechanical hardening and decreases the plasticity [3].

The goal of the present paper is to establish the Mg content effect in annealed Al-Li-Cu-Mg-Zr alloys on their plasticity during cold deformation and also to determine the plasticity dependence on such structural factors as phase composition, phases volume fraction and alloying elements content in the solid solution.

Experimental Procedures

We studied four alloys on the base of Al-1.9Li-1.8Cu-0.1Zr in wt.% into which 1.0Mg (the alloy no.1 complies with the commercial 1441 alloy); 1.6Mg (the alloy no.2); 2.2Mg (the alloy no.3); 2.6Mg (the alloy no.4, complies with the commercial 1430 alloy) were additionally introduced. Ingots with the diameter of 70 mm were cast in the metallic water-cooled mould, homogenized according to the temper: 793 K, 24 hours; bars of 15 x 60 mm were extruded at 713 - 723 K to with the following rolling at 673 K into the sheets with the thickness of 7 mm. The rolled sheets annealing was carried out at the temperatures of 673 - 793 K with the exposure of 2 - 6 hours and the cooling with the rate of 30 K/hour, which simulates the coil cooling rate.

There are no standard laboratory methods for evaluating the sheets plasticity under cold coil rolling conditions. The laboratory test results obtained by different methods should be compared with the material plasticity under production conditions. Such characteristics as elongation or reduction of area during tensile tests poorly correlate with it. When producing Al-Li cold-rolled sheets under commercial conditions it was found that the 1441 sheets had the plasticity close to that of conventional aluminum alloys after annealing while the crack initiation in the 1430 sheets took place with the lesser reduction and the larger number of intermediate annealings was required. The laboratory methods for plasticity evaluation during cold deformation used for these alloys in the present work allowed to obtain the results complying with the commercial production.

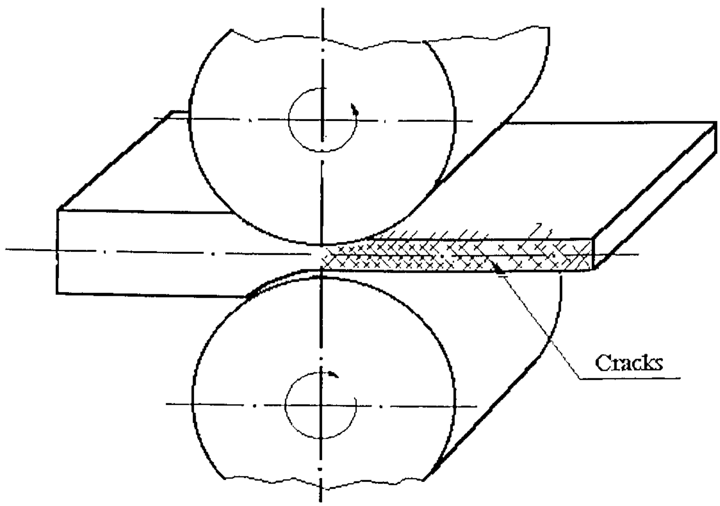


Fig.1. A schematic representation of specimens failure when determining the plasticity by card rolling method.

The methods of plane compression [2] and card rolling were used. Specimens edges were milled prior to testing. In case of plane compression the plasticity was evaluated by the maximum deformation degree value, at which cracks didn't appear yet. The values of $\varepsilon_{cr}=50\%$ and $\varepsilon_{cr}=20\%$ were experimentally obtained for 1441 and 1430 alloys, respectively, after annealing according to optimum tempers, which complied with the difference in the plasticity of these alloys during cold coil rolling. The second method included the card cold rolling with use of the laboratory rolling mill and the set of constant deformation degrees in one pass, ε_i,%, to crack initiation on the side milled edge (Fig.1). The appropriate total deformation degree ε^{Σ}_i,% was defined and the relationship between

$\varepsilon^{\Sigma}_{i},\%$ and $\varepsilon_i,\%$ (Fig.2) are plotted. As a rule, with the growth of $\varepsilon_i,\%$ under constant rolls rotation speed $\varepsilon^{\Sigma}_{i},\%$ is decreased due to deformation rate increase. The plasticity was evaluated by position of the approximating line which was characterized by two parameters: the value $\varepsilon^{\Sigma}_{25},\%$ with the deformation degree of 25% in one pass and the difference ($\varepsilon^{\Sigma}_{5},\%$ - $\varepsilon^{\Sigma}_{25},\%$). The higher plasticity is the larger $\varepsilon^{\Sigma}_{25},\%$ and the lesser difference ($\varepsilon^{\Sigma}_{5},\%$ - $\varepsilon^{\Sigma}_{25},\%$). The values of $\varepsilon^{\Sigma}_{25},\%=75$ and $\varepsilon^{\Sigma}_{25},\%=33$ were obtaihed after optimum annealing for 1441 and 1430 alloys , respectively, and ($\varepsilon^{\Sigma}_{5},\%$ - $\varepsilon^{\Sigma}_{25},\%$)=17 and 27 (Fig.2).

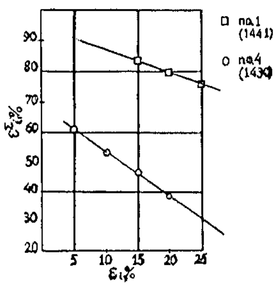


Fig.2. Plasticity values of alloys nos. 1 (1441) and 4 (1430) specimens annealed according to optimum tempers by card rolling method.

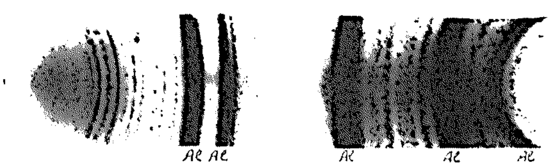


Fig.3. X-ray photograph of the annealed no.4 (1430) alloy. CrK_{α}.-radiation. The α-solid solution and T_2.-phase lines.

The determination of annealed specimens phase composition was carried out by monochromatic CrK_{α}-radiation exposure of flat section specimen at an angle of 15-20 degrees in Debye camera. The evaluation of the method sensitivity on technical aluminum showed that it is capable to record to 0.5% of excessive phases volume fraction. The full set of T_2-phase ($Al_6Cu(LiMg)_3$) lines including lines with the table intensity of 6-10% from the maximum one was seen in the X-ray photograph (Fig.3) of the no.4 alloy annealed specimen with the phase volume fraction of approximately 7% (according metallographic data).

The quantitative evaluation of the relative T_2-phase volume fraction was performed on powder specimens by X-ray method. The integral intensity was defined diffractometrically by means of monochromatic CoK_{α}-radiation. Three lines of T_2-

phase (611), (710) and (940) and five matrix lines (111), (200), (220), (311), (331) were exposed by points. The calculation was carried out with the following formulae:

$$K_m = 1/n \sum_{i=1}^{n} I^i_{ms} / I^i_{mr} , \qquad (1)$$

where I^i_{ms} and I^i_{mr} - integral intensities of i-matrix line for the specimen and reference standard, n - matrix line number (n=5), K_m - the specimen matrix lines intensity factor relative to the reference standard.

$$K'_p = 1/n \sum_{i=1}^{n} I^i_{ps} / I^i_{pr} , \qquad (2)$$

where I^i_{ps} and I^i_{pr} - integral intensities of i-phase line for the specimen and reference standard, n - phase line number (n=3), K'_p - the specimen phase lines intensity factor relative to the reference standard.

$$K_p = K'_p / K_m , \qquad (3)$$

where K_p - T_2-phase relative quantity in the specimen as compared to the reference standard. The T_2-phase volume fraction in separate points was calculated metallographically by point method. Cu and Mg content in the excessive phases and matrix was defined by electron probe microanalysis (EPMA) and also by lattice spacings (a) measurements. In order to increase the measurement accuracy, W pure powder was applied on specimens surface as a reference standard; the $(331)_{Al}$, $(420)_{Al}$ and $(222)_W$ lines were recorded; the specimen temperature was measured with the accuracy of 0.5 K and it was taken into account during calculation. The determination accuracy is 5×10^{-5}nm.

Results and Discussion.

The studied alloys have either nonrecrystallized or partially recrystallized structure with the recrystallization degree of less than 5% after annealing. The phase analysis showed that all of them contains only α-solid solution and T_2-phase precipitates after annealing with slow cooling. The transmission electron microscopy study confirmed this conclusion - the evident δ'-phase particles weren't revealed. The EPMA results - Cu and Mg content in and matrix of annealed nos. 1 (1441) and 4 (1430) alloys are given in Table I.

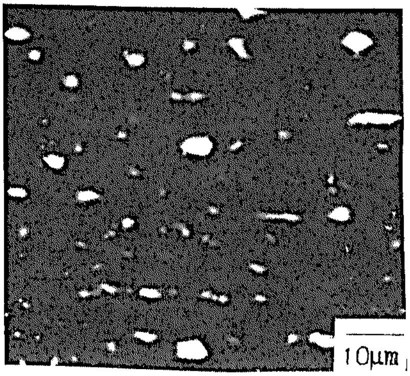
Cu and Mg concentration in the phase slightly depends on the annealing temperature. T_2-phase particles along with the high Cu content (and also Li which is not determined by EPMA method) have the higher Mg content compared to the matrix. With Mg concentration increase in the alloy from 1.0 up to 2.6%, Mg content in the matrix is increased by 3 times, in the phase - by 1.5-2 times, and Cu concentration in the phase is increased by 1.5 times. It is evidently that almost all copper, available in alloys, transits into a T_2-phase s a result of annealing. Let's calculate the possible T_2-phase amount as it was made in [2]. The studiet four alloys contain 0.7-0.8 at. % Cu. Hence [2], the highest

Table I. EPMA results.

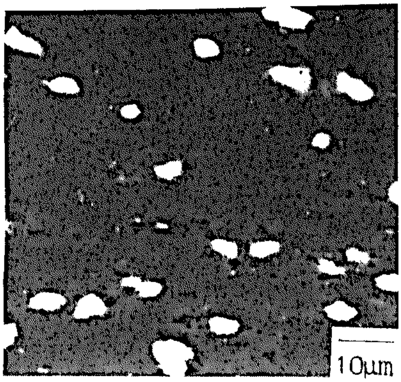
Alloy	Temper	Relative radiation intensity			
		Cu		Mg	
		matrix	T2-phase	matrix	T2-phase
no.1,1441	Annealing 673 K, 2h.->*	0.24%	25%	0.8%	2.8%
	793 K, 2h.->	0.48%	25.5%	0.9%	2.2%
no.4,1430	Annealing 673 K, 2h.->	0.29%	35.5%	2.9%	4.7%
	793 K, 2h.->	0.21%	32.3%	3.3%	4.7%

* --> cooling rate of 30 K/h.

possible T_2-phase amount is 7-8 mol.%, taking into account its chemical composition. Not taking into consideration a slight difference in average phase and matrix atomic volumes, we obtain the upper limit of T_2-phase volume fraction of 7-8 vol.%. In this case the T_2-phase contains 2.0-2.1 at.% Li, and 4.5-5 0 at.% Li is left in the solid solution, i.e. 1.3-1.4 wt.% Li and the greater part of Mg, available in the alloy.



a



b

Fig.4. Microstructure of no.1 (1441) alloy a) and no.4 (1430) alloy b) after annealing 753 K, 2h and cooling rate 30 K/h. SEM.

The metallographic studies (Fig.4) showed, that T_2-phase particles in annealed alloys have the sizes from 0.5 to 6 μm in transverse direction. The average partical sizes in transverse direction is 1.5 - 3.5 μm. The higher annealing temperature is the larger particle sizes. Particles initiate and grow both at grain and subgrain boundaries and also in subgrain volume on β'-phase ($Al_3(ZrLi)$) dispersoids. The particles volume fraction for different alloys and annealing tempers were changed in the limits from 6.0 to 8.5%. Cracks at cold rolling (Fig.1) and plane compression initiate in zones of the maximum shear deformation inside T_2-phase particles or at the interface surface and don't show some connection with grain boundaries. Fig.5a shows that the lattice spacing is almost linearly grown with Mg content increase in the solid solution and quenched nos.1-4 alloys. It was marked, that alloying components are in the solid solution after quenching when comparing dependence an Mg,Cu and Li concentration in binary solid solutions [4] (dotted line in Fig.5a). The greater T_2-phase precipitates at annealing, the higher **a** value should be. It is seen from Fig. 5b, tha **a** t is increased in the process of annealing as compared to the quenched alloys but the difference between alloys is retained. The basic Mg portion, containing in the alloy, is left in the solid solution.

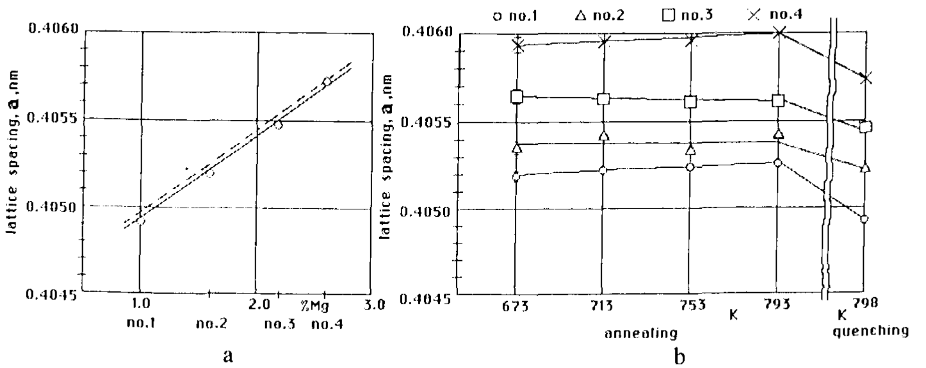


Fig.5. Plot of lattice spacings, **a** , nos. 1 - 4 alloys versus content Mg in alloys and tempers. a) **a** for quenched specimens; dotted line is calculated as if Mg, Li and Cu are in the solid solution [4], b) **a** for annealed specimens.

The measurement results of relative T_2-phase amounts in annealed alloys by X-ray method are shown in Fig.6. The changes are comparatively not large - in the limits of 30% as far as the T_2-phase amount is determined, mainly, by Cu and Li content in the alloy, which is approximately the same in the studied alloys. Let's compare the measurements results of plasticity values at cold deformation with structural studies data. Fig. 7 and 8 show the dependences of the plasticity value at plane compression , on the structure parameters of annealed specimens, determined on the base of measurements of **a** Mg content in the solid solution (Fig.7) and T_2-phase relative amount (Fig.8). Hence, the plasticity decrease correlates better with % Mg content in the solid solution than with T_2-phase amount increase. One should take into account that there is also 1.3-1.4

wt.% Li in the solid solution additionally decreasing the plasticity. The T_2-phase volume fraction in the annealed alloys has lesser effect upon the plasticity but it also should be taken into account for every alloy when analyzing the annealing temper effect. The plasticity is decreased with annealing temperature increase for nos.1 (1141) and 2 alloys. Perhaps, it is associated with T_2-phase particles coarsening. For the no.4 (1430) alloy the plasticity is increased with annealing temperature raise and it is followed by some decrease of T_2-phase amount (Fig.6). Based on these ideas the necessary annealing temper with slow cooling was recommended for every alloy. The mechanical properties of hot-rolled sheets were determined for all four alloys after solution treatment, water quenching and artificial ageing. The following values were obtained: UTS 470-510 MPa, YS 370-410 MPa, El 9-13%. Mg content decrease in the alloy no.3 doesn't lead to the perceptible decrease of strength properties as compared to the no.4 (1430) alloy but this alloy has ε_{cr} equal to 35% after annealing according to the optimum temper while the no.4 (1430) alloy has only 20%. Thus, it is recommended to decrease Mg content in 1430 alloy by 0.4% which allows to increase the alloy plasticity under cold coil rolling conditions without significant decrease of strength properties.

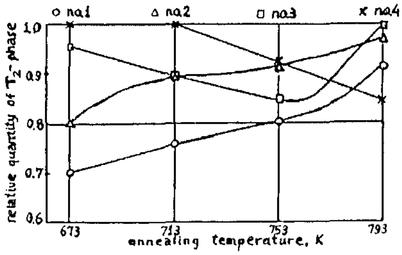


Fig.6. Plot of relative quantity of T_2-phase versus annealing temperature for an nos. 1 - 4 alloys.

Conclusion

With Mg content increase the plasticity is distinctly decreased during cold working of annealed alloys. For an alloy Al-1.9Li-1.8Cu-1.0Mg-0.17Zr the plasticity values are similar to those of conventional commercial aluminium alloys. The plasticity values of the alloy containing 2.6% Mg with the same level of Li and Cu are lower by two or three times. The T_2-phase precipitates initiate in all alloys after annealing at 693-793 K, 2h. with the cooling rate of 30 K/h. The basic amount of Mg and considerable amount of Li remain in the solid solution. The plasticity decrease of the annealed alloys correlates well with Mg and Li content increase in the solid solution and to a less extent with T_2-phase volume fraction. In order to obtain the best plasticity of alloys with different Mg content the annealing conditions are recommended.

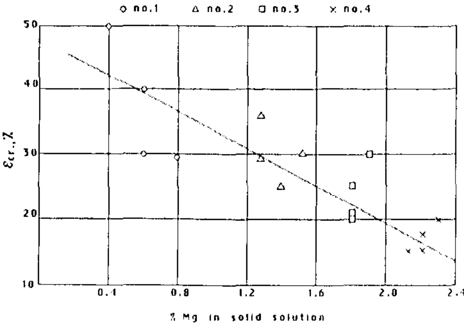


Fig.7. Plot of plasticity values $\mathcal{E}_{cr}$ versus % Mg in solid solution for an annealed nos. 1 - 4 alloys.

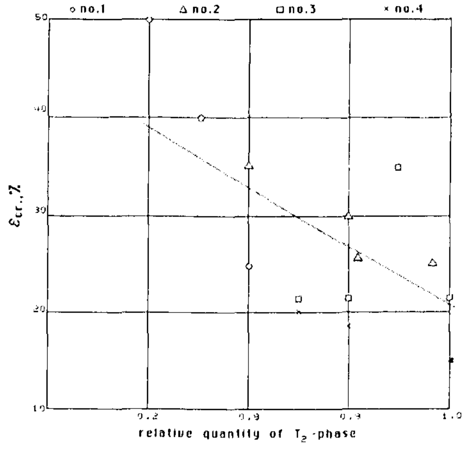


Fig.8. Plot of plasticity values $\mathcal{E}_{cr}$ versus relative quantity of T_2-phase for the annealed nos. 1 - 4 alloys.

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