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Structural Evolution in Aluminum-Copper-Lithium-Magnesium Alloy Sheets During Processing.

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Abstract. The texture and microstructure of the pressings and hot rolled sheets produced from Al-4.1 wt. %Cu-1.1 wt. %Li (S1) and Al-4.6 wt. %Cu-1.4 wt. %Li (S2) alloys with alloying addition of Ag and Mg investigated. The ingots (70 mm in diameter) after casting and homogenization were subjected to extrusion onto the strips with section 11×60 mm after heating at 400-440ºC, and than to the hot rolling across the extrusion direction up to 4 mm in thick. The sheets were subject to heat treatment under regime of T8. In the pressings and sheets produced by extrusion and rolling of S1 alloy the multi-component {110} <112> + {123} <634> + {112} <111> texture is developed. The main strengthening phases in these materials consist of dispersion particles of T_1 in form of plates and particles of θ' in form of rods. It was observed unusual for high-strength Al-Cu-Li alloys texture in the S2 alloy sheets in which the main texture component was (110) <111>; the thermal hardening effect was achieved mainly by means T_1 precipitations. The electron microscopy data indicated that a significant contribution to the deformation of a S2 alloy originated from the localized shear deformation, which stimulated the of T_1 plates formation on the block boundaries.

1. Introduction

Aluminum-copper-lithium alloys with additions of Mg and Ag considered as very promising in aerospace industry [1]. They characterized by the excellent combination of strength and plastic properties, well weldability and successfully applied for the manufacturing of commercial extrusions, rolled plate and sheets [1]. High strength characteristics of these materials after heat treatment primarily is achieved due to dispersed T_1 (Al_2CuLi) and θ′ ($CuAl_2$) precipitations which formed as in artificial as in natural aged states. The strength of Al-Cu-Li alloys materials strongly depends on the relative content of copper and lithium; the maxima value of strength is in the concentration range ~ 1.1÷1.4 wt. % Li [2]. With further increasing of the lithium concentration the decreasing of the strength characteristics associated with formation of δ' (Al_3Li) particles, reducing the content of the main strengthening phase T_1, observed. Alloying addition of silver in these alloys considered as a improving of the thermal stability factor.

T_1-phase has a hexagonal structure with a=4.954 Ǻ, c=9.327 Ǻ [3, 4]. The T_1-phase nuclei of the critical size are composed from the five atomic nets which packed along [0001]-direction as *ABACA*, where *A* – the net enriched with aluminum and *B*, *C*-with lithium. The mechanism of theT_1-phase plates grow is stepped; the step height is equal to the unit cell parameter. The hexagonal shaped T_1-plates (hexagons) observed by electron microscopy, as thin platelets appeared on the {111} α-matrix planes. The density of T_1-phase precipitations in the aged alloys can reach ~1000 m^{-3}. The in the quenched, naturally and artificially aged materials are observed in the electron microscopy experiments as a discs with the form factor k>40, lying on the {100} α-matrix planes. According to [4, 5] the θ′-phase particles have the tetragonal lattice with a=4.04 Ǻ, b=5, 8 Ǻ. At the early stage of artificial aging in the Al-Cu-Li alloy materials the δ' precipitations usually observed and in the alloys with high lithium content quasicrystalline phase T_2 (Al_6CuLi_3)

precipitations are registered [4].

The orientation of strengthening particles of T_1 and θ' phases formed during the aging, obviously, strongly depends on the type of crystallographic texture of α-matrix. In the extruded and rolled Al-Cu-Li materials as the most intensive usually developed the following texture components: **Bs** {110} <112>, **Cu** {211} <111>, **S** {123} <111> and the components of recrystallization with the most intensive {001} <uv0>-type component [5].

In this work the evolution of structure of the material extruded strips of two Al-Cu-Li alloys with composition closed to composition with maximal of strength characteristics but differing in Cu and Li contents were studied in dependence on hot-rolling and heat treatment parameters

2. Experimental

The chemical composition of alloys presented in the table 1.

Table 1. *The chemical composition of the investigated alloys.*

Samples marks	Alloying additions, wt.%				
	Cu	Li	Mg	Ag	Zr
S1	4.08	1.09	0.31	0.38	0.1
S2	4,66	1.38	0.51	0.44	0.1

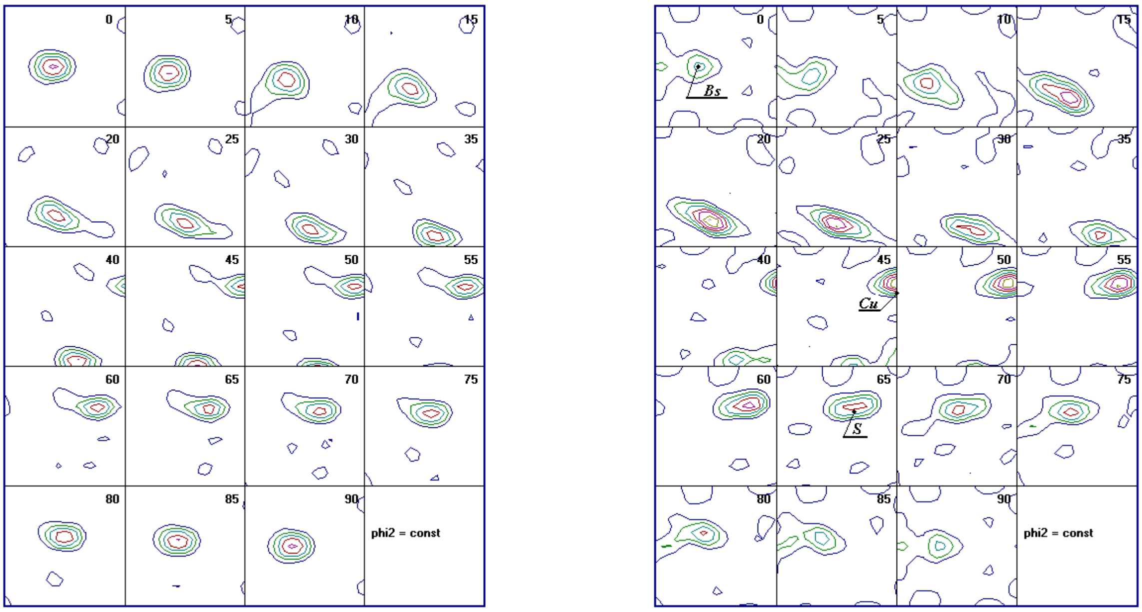
The ingots of alloys with diameter 70 mm cast in water cooled mold and homogenized at 450°C during 16 hr + 500°C, 5 h. They pressed then to the strips 11x60 mm in cross sections after heating at 400-440°C for 5 h. From these strips, we cut out samples that hot rolled into sheets with the size 4x200x400 across to the pressing direction. Hot rolled sheets heat-treated under the following regime: heating for quenching 510-525°C, cooling in water and aging at 160°C during 30 hr. The chemical analysis of samples cut from middle part of the pieces carried out by atomic emission method with the inductive plasma spectrometer model "Ultima -2".

The texture was studied using the samples cut from the middle part of extruded strips and sheets so way that the plane of X-ray study was corresponded to the plane parallel to the strips and sheets surface. The thickness of samples decreased by polishing and etching from both sides up to value of 0,25 mm. The texture investigated on the base of X-ray experiment using diffractometer DRON-7-PGTM in CuKα-radiation with pole figures (PF): (111), (200), (220) and (113). The orientation distribution function (ODF) constructed using the Texx-2007 program [6]. X-ray diffraction analysis (XRD) performed using DRON-7 diffractometer in the CuKα-radiation with the graphite monochromator installed on the reflected beam. Optical microscopy investigation of the microstructure fulfilled using the program NEXYS Image Expert Pro 3. The structural studies by transmission electron microscopy performed on a JEM-1000 microscope (JEOL) at an accelerating voltage of 500 kV. The samples, discs 3 mm in diameter, cut by an ultrasonic installation Ultrasonic Disc Cutter (GATAN). Their thickness was reduced by jet electropolishing in a solution 25% HNO_3+75% CH_4OH at 10°C, a current of 0.02 A per side and a voltage of 20 V. After polishing (~ 20 min.) the samples were washed in distilled water and dried. The mechanical properties received in tensile test carried out in accordance with usable standards of Russia.

3. Results

3.1. The structure of pressings and sheets of S1 alloy

The texture of S1 alloy extruded strips in the middle part of section has the multi-component character (fig 1a). The dominant is the **Bs** {110} <112> component, the **S** {123} <634> and **Cu** {112} <111> components are rather weak. Maxima of orientation density of the components mentioned above blurred on ODF sections and in the blurred regions; the several other components localized. Thus, in the blurring region of the **S** {110} <112> component the component **Ex₁** {110} <111> is placed, and at the same time the maximum on the φ_2=65° section is formed perhaps in result of the **S** {123} <634> and **Ex₂** {123} <111> components blurring.

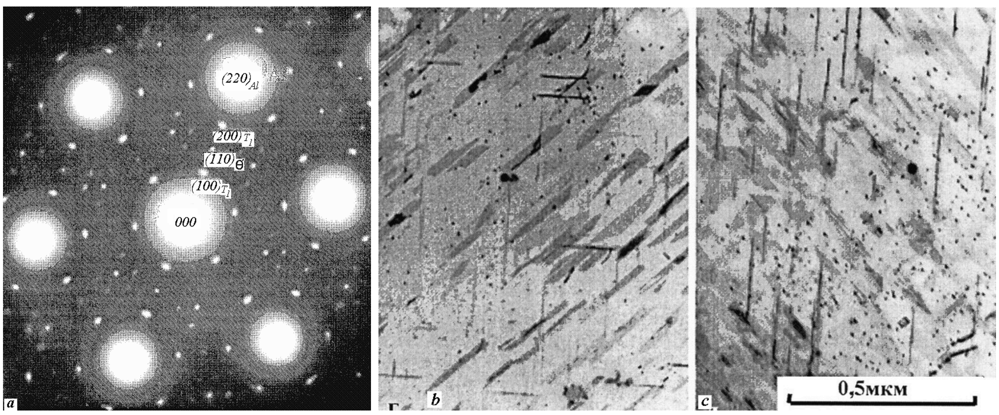


a ***b***

*Fig.1. ODF section of middle part for **a** - pressings, **b** – hot rolled sheets produced from S1 alloy.*

The rolling of the extruded strips leads to a marked redistribution of orientation intensity on the ODF sections (fig 1*b*). The main maximum on the φ_2=0° section is significantly diminished, its position became exactly corresponds to **Bs** {110} <112> component position. The maximum nearby **Cu** {112} <111> slightly shifted to the region of the small Φ angles. Maximum on φ_2=65° section in the rolled sheets corresponds to **S** {123} <634> component position. In the texture "tube" formalism such changing indicate that the deformation during rolling developed through the α-tube type [7] what confirmed also by diminishing of the **Bs** component and increasing of **S** component intensity.

Electron microscopy study of the middle layers S1 alloy sheets after heat treatment revealed the presence of T_1 and θ′ phases semicoherent precipitations (fig.2). From fig 2*a*, which shows the



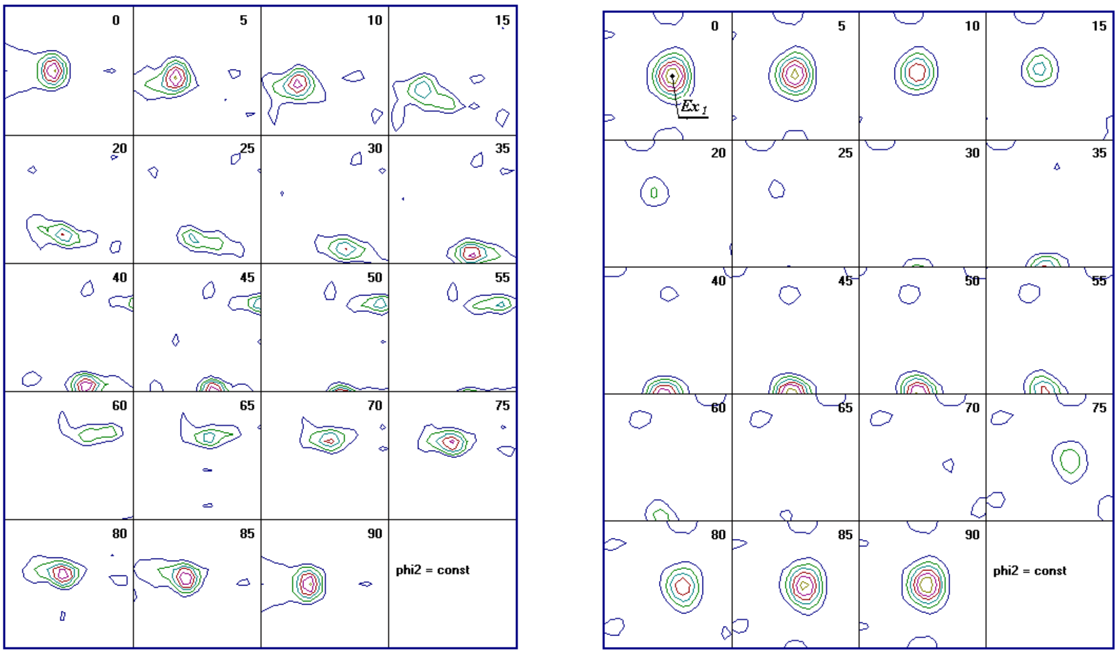
a ***b*** ***c***

Fig.2. a – pattern of diffraction, b, c – electron microscopic images of middle part of S1 alloy sheets.

electron diffraction patterns along [111] direction of α matrix grain, it is clear that between α, T_1, θ' phases the orientation relationship: $[10\text{-}10]_{T1}//[110]_\alpha$ and $[110]_\theta//[110]_\alpha$ observed. In fig. 2*b*, 2*c* the different orientation variants of T_1 phase plate precipitations and θ' phase rods could be seen.

3.2. The structure of pressings and sheets of S2 alloy

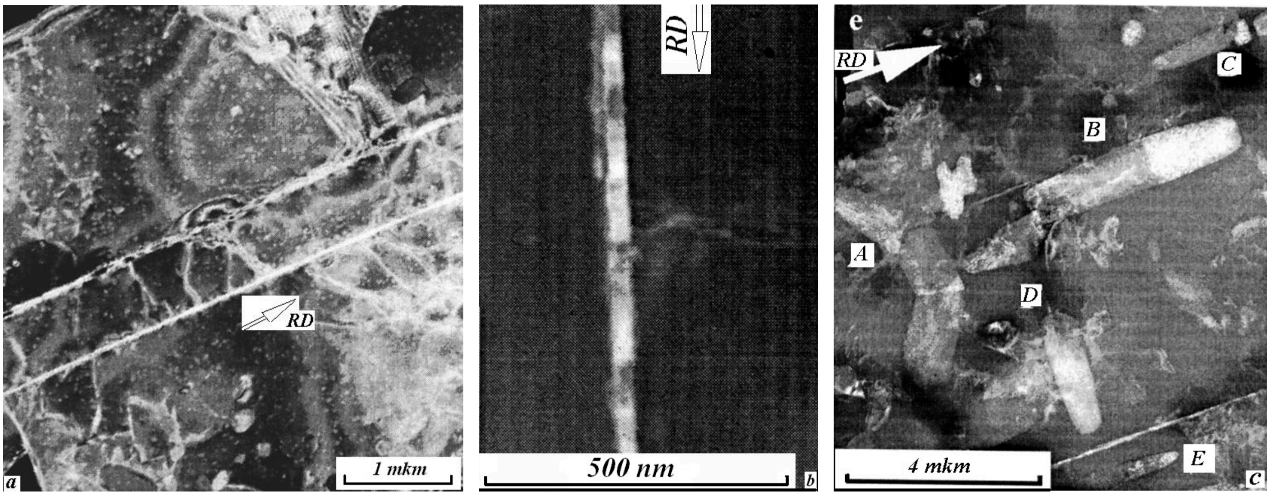
The textures of the S2 and S1 alloys pressings are similar (fig. 1*a* and 3*a*) but in the case of S2 alloy, the component **Bs** even is more pronounced. The texture of hot-rolled S2 alloy sheets significantly different from the texture of S1 alloy sheets (fig. 1*b* and 3*b*). In the S1 alloy it has a multi-component character, and in the sheets of S2 alloy the texture is nearly single-component with the main contribution from $\mathbf{Ex_1}$ {110} <111>. During subsequent heat treatment, the intensity of the texture significantly diminished, but its single-component character remained.



a *b*

*Fig. 3. ODF section of middle part for **a** - pressings, **b** – hot rolled sheets produced from S2 alloy.*

According to the results of the electron microscopy study significant differences between the structures of the S2 and S1 alloys pressings and sheets appeared. In the S2 alloy materials the amount of θ'-phase particles much smaller than that in S1 alloy; the δ' particles were not found. As it follows from the electron microscopy study the main strengthening system in S2 alloy material arising in the process of aging represented by the precipitations of the T_1 phase in form of plates (fig. 4*a*). Along with dispersed T_1 particles the rough plate of T_1 phase inherited in these materials apparently from the ingot observed (fig. 4*b*). A characteristic feature of the microstructure of S2 alloy materials is the slip bands formation with direction corresponds to the rolling direction (fig. 4*a*). On the boundaries of these bands, the oriented particles of T_1 phase observed. This is could be quite expected fact as it was found earlier that the T_1 phase formation stimulated by dislocation [10]. The electron microscopy study of S2 alloy pressings and sheets revealed the presence of icosahedral T_2-phase precipitations in these materials. In fig. 4*c,* several such precipitations (A - E) in S2 pressing presented; part of them destroyed during the strip pressing. Identification one these icosahedrals was carried out by us in [9].



a ***b*** ***c***

Fig.4. a – a slip bands in microstructure of the S2 pressing, b – rough plate of T_1-phase in microstructure of S2 sheet, c – T_2 crystals in material of S2 alloy pressing.

The results of measuring of S1 and S2 alloy sheets strength characteristics presented in the tab. 2

Table 2. *Yield strength $\sigma_{0.2}$, ultimate tensile strength σ_B, elasticity module E and impact toughness a_k of hot-rolled sheets produced by rolling of S1 u S2 alloys ingots.*

alloys marks	$\sigma_{0.2,}$ (MPa)	σ_B, (MPa)	E, (MPa)	$\boldsymbol{a_k}$, (кJ/м^2)
S1	530	590	80000	150
S2	480	560	80000	143

3.3 Discussion

The important result of this work is that the alloy S2 of Al-Cu-Li system with optimal lithium concentration (1.3-1.4%, see part 1) as the main strengthening phase contains T_1-phase and θ'-phase precipitations are not available in it. As it is known, the phase precipitation processes in these alloys developing during aging are a rather complex in its nature; the precipitations of various phases (δ', T_1, θ') are nucleated and grew with aging time [10]. The δ'-particles are precipitated at the early stage of aging. With increasing of the time of aging the volume percent of δ' decreased, as the volume percent of T_1 and θ' increased. With the further increasing of aging time the process of precipitation of T_2 phase particles occur that leads to significant decrease in strength, since T_2 precipitate are formed at the expense of more potent strengthening phase T_1. In addition, T_2 particles precipitated along the grain boundaries what results in embrittlement of the material. Therefore the time and temperature of aging are chosen so that the vanishing of δ'-phase was completed, and the precipitation of T_2 particles not yet begun. One of such optimal aging regime is T8: 160°C (~ 30 h) after quenching at 510÷525°C [1]. In the S1 alloy sheets approximately the same volumes of T_1 and θ'- particles are contained after this heat treatment. These sheets have the significantly higher values of the strengths characteristics, in compare with S2 alloy sheets, where θ'-phase particles are practically lacking.

The unusual S2 alloy microstructure nature should apparently linked with the high content of copper. The texture of the sheets produced from this alloy also is not conventional for high-strength Al-Cu-Li alloys. It has usually a multi-component character and includes a main, as noted above, **Bs**, **S** and **Cu** components whereas the distribution of orientation density at the ODF section constructed for S2 alloy sheets well described by single-component of Ex_1. Taking into account that the deformation of S2 sheets material developed with a slip bands formation, we can assume that the shear type of deformation in the area bands boundaries stimulates the T_1 plates formation by mechanism proposed in [4]. According to this work, the nucleation and growth of T_1 plate are stimulated with the structural change that may be accomplished by passage of two Shokley partial dislocations $a/6<112>$ on adjacent $\{111\}_\alpha$ matrix planes. The passage such paired dislocations manifests itself in changing stacking sequence net from cubic *ABC* to *ABAC*, which is characteristic of T_1 phase and resulting in growth ledges which are four $\{111\}_\alpha$ matrix planes high. It is clear that the shear stresses arising during deformation on the bands boundary stimulate this process.

Summary

1. This structure investigation of the pressings and hot-rolled sheets, produced from the aluminum alloys 4.1% Cu, 1.1% Li and 4.6 %Cu, 1.4% Li containing of Mg and Ag additions shows the marked differences in microstructure and texture of these materials.

2. The type of 4.1% Cu, 1.1% Li alloy texture represented by **Bs** {110} <112>, **Cu** {211} <111>, **S** {123} <111> components is in agreement with results of earlier investigations of the high-strength Al-Cu-Li alloys. The strengthening effect in these materials due to artificial aging connected with the fine T_1 and θ' phases.

3. In the 4.6% Cu, 1.4% Li alloy hot-rolling sheets the unusual nearly single-component texture $\mathbf{Ex_1}$ {110} <111> is developed. As a base strengthening particles after artificial aging in this alloy, the dispersed plates of T_1 phase could be considered.

4. Characteristic feature of the microstructure of the 4.6% Cu, 1.4% Li alloy pressings and sheets is the slip band formation. Precipitations of the T_1 phase plates observed on the boundaries of these bands stimulated perhaps by dislocation mechanisms of deformation.

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