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The influence of long-lasting annealing on microstructure of AlCu4Ni2Mg2 alloy

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Materials

ABSTRACT

Purpose: of this paper was to determine the influence of long-term annealing at elevated temperature on the microstructure and mechanical properties of AlCu4Ni2Mg2 alloy.
Design/methodology/approach: The microstructure was observed using optical light (LM), scanning (SEM) and transmission (TEM) microscopy. The mechanical properties were determined on a standard tensile test machine.
Findings: It was found that after long time hold at elevated temperature (523 K) the degradation of microstructure of alloy was observed. The microstructural changes consist in increase of size of hardening phases precipitates (Θ'-Al2Cu) and changing its shape. These phenomena cause decrease in the mechanical properties of the alloy.
Research limitations/implications: In order to complete obtained results it is recommended to perform further investigations of behaviour of AlCu4Ni2Mg2 alloy in 573 K and 623 K corresponding to the maximum values of temperature at which structural elements of piston engines made of aluminium alloys operate.
Practical implications: From a practical point of view it is important to realize, that however the Cu (about 4%) and Ni (about 2%) additions significantly influence increasing of mechanical properties of aluminium alloy, nevertheless don't protect against the degradation of its microstructure and finally from decreasing of strength during machine elements operation.
Originality/value: This work has provided essential data about microstructural changes of aluminium alloy proceeding during elements of piston engines operation.
Keywords: Metallic alloys, Electron microscopy, Microstructure, Mechanical properties

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1. Introduction

The progress of aircraft industry is closely connected with production and application of aluminium alloys which are characterized by lower density and better mechanical properties than up to now applied alloys. It may be reached by application of two major processes: addition of alloying elements during the melting and treatment of liquid alloy (refining, modification) and use the adequate heat treatment [1-2]. The casting aluminium alloys 2xxx group containing Cu with addition of Mg and Ni are widely used in the world aircraft technique. The typical quaternary AlCu4Ni2Mg2 alloy are characterized by good hardness and strength at elevated temperature [3-6].

The intermetallic phases Al_6Cu_3Ni and Al_2CuMg forming during both primary crystallization and hardening process are responsible for improvement oh these properties. The mechanism of hardening in binary Al-Cu alloys (both cast and wrought) is known and described precisely in literature. It is assumed that supersaturated solid solution α(Al) decomposition proceeds in the same way as in the other precipitate strengthened aluminium alloys (for ex. Al-Cu-Mg, Al-Si-Cu or Al-Mg-Si) [7-9]. The course and kinetics of ageing process of solid solution are very interesting from practical point of view – the first stages lead to significant increase of mechanical properties. The maximum of Al-Cu alloys hardening results from transformation in situ of GP zones into intermediate θ" phase. Along with increasing of ageing temperature the decreasing of solid solution α(Al) hardness is observed. It is the effect of preciptation of equilibrium θ phase on the grain boundaries or in the neighbourhood of the interface matrix/θ' phase. The long-lasting annealing leads to degradation of microstructure via coagulation and coalescence of hardening phase particles (the hardening effect achieved during annealing is lost) [10-12].

2. Material and experimental

The investigation was carried out on the 2xxx group casting alumium alloy AlCu4Ni2Mg2. The chemical composition of the alloy is: 4.3% Cu, 2.1% Ni, 1.5% Ni, 0.3% Zn, 0.1% Fe, 0.1% Si, Al bal. The alloy was subjected to heat treatment T6: solution treatment $793^{\pm5}$K/5h/water cooling and artificial ageing at $523^{\pm5}$K/5h/air cooling, and following long-term annealing at $523^{\pm5}$K for 100, 150, 300, 500 and 750 hours. The microstructure of examined alloy was observed using an optical microscope Nikon Epiphot 300 on polished sections etched in Keller solution (2 ml HF + 3 ml HCl + 20 ml HNO_3 + 175 ml H_2O). Morphology of microstructure constituents was determined using the scanning electron microscope Hitachi S-3400N with EDS system and transmission electron microscopes Jeol-2100 and Tesla BS-540. The thin foils were prepared by electrochemical polishing in reagent: 260 ml CH_3OH + 35 ml glycerol + 5 ml $HClO_4$ using Tenupol-3 and automatic sputter coater Cresington 108auto. The tensile tests were performed on smooth cylindrical specimens according to PN-EN 1002-1 using Instron 8801 testing machine.

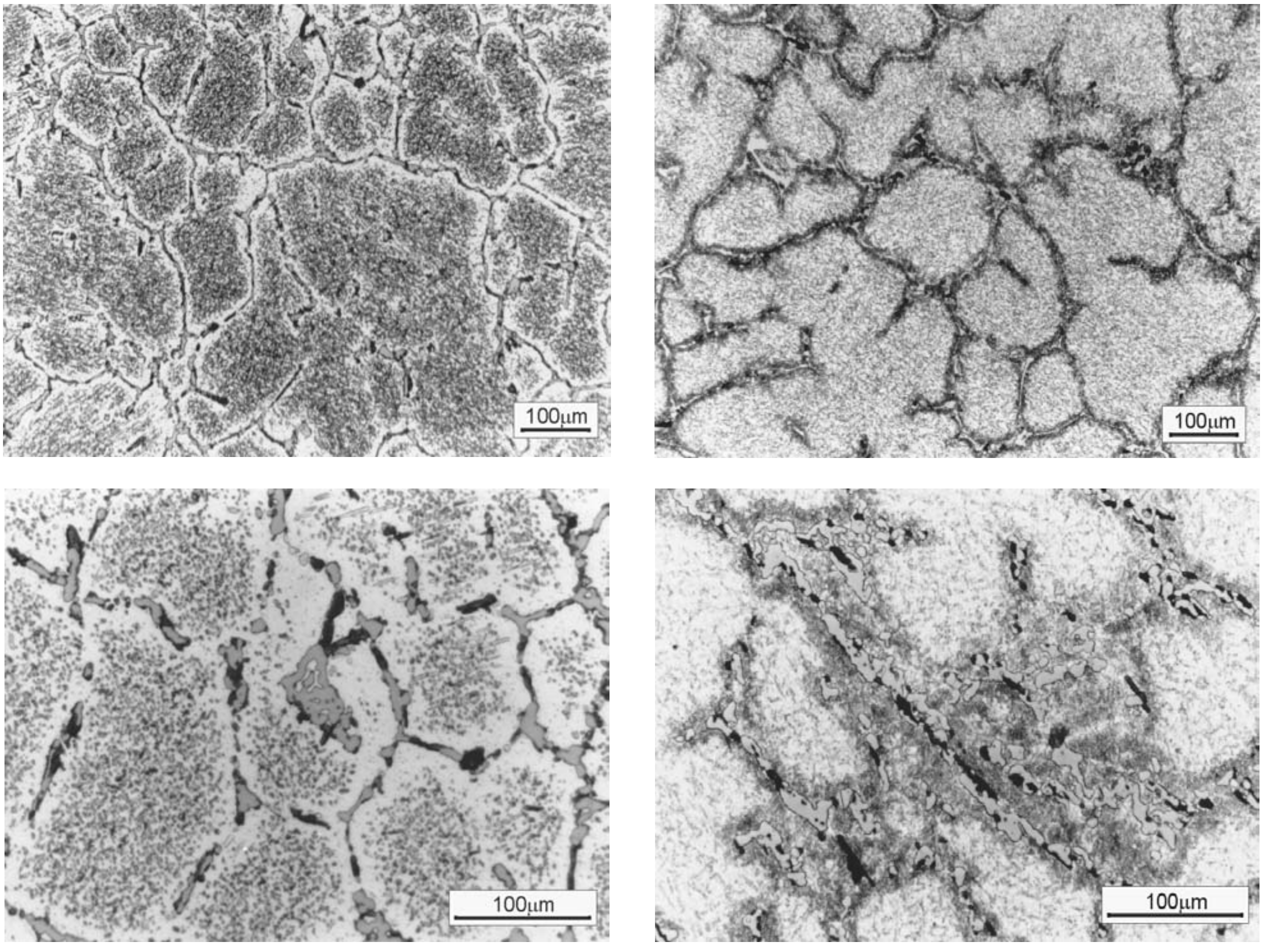


Fig. 1. Microstructure of AlCu4Ni2Mg alloy in T6 condition

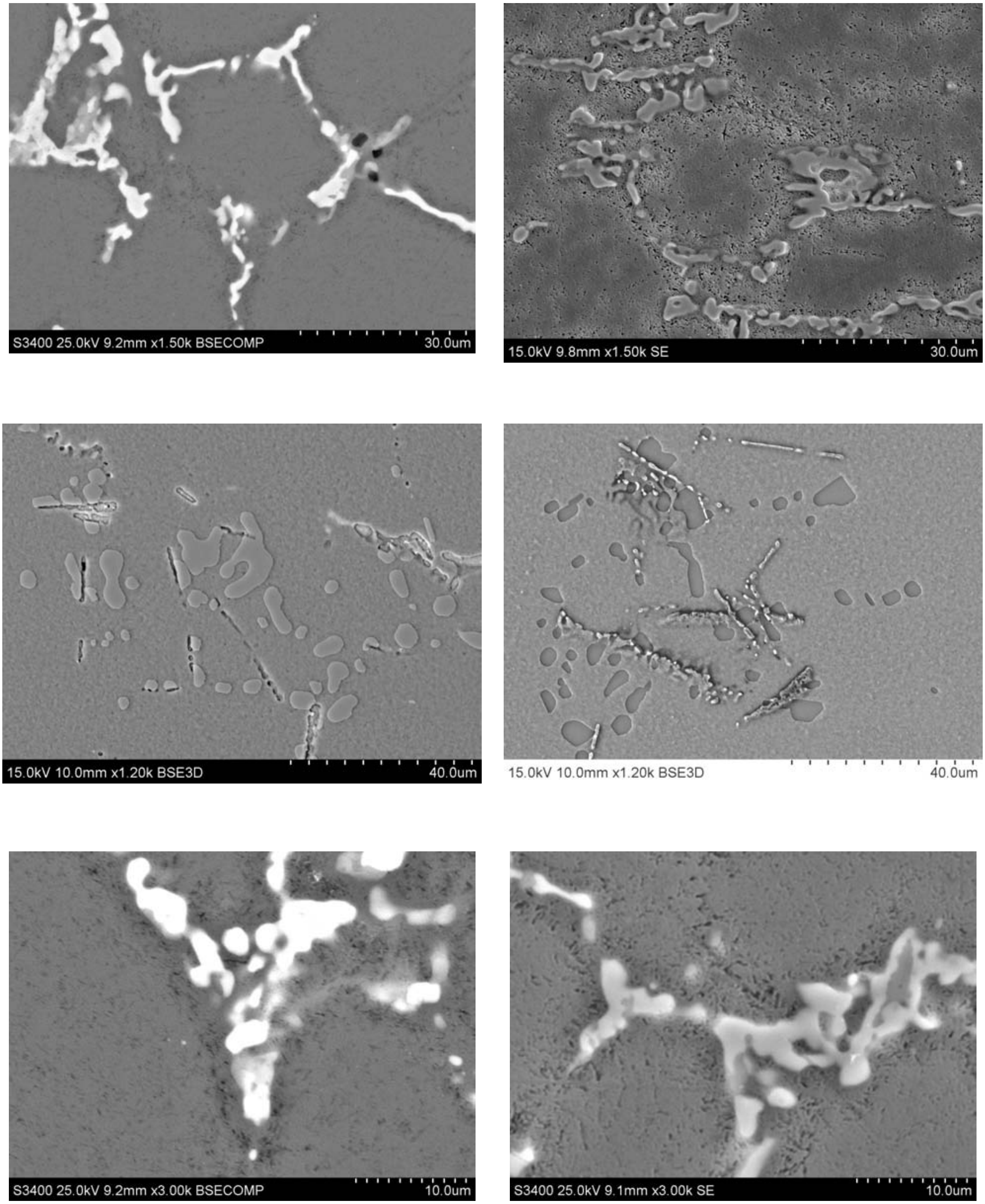
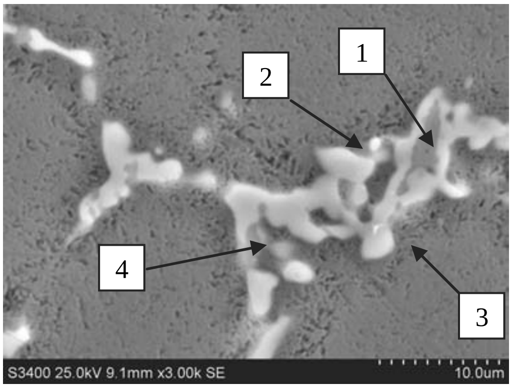
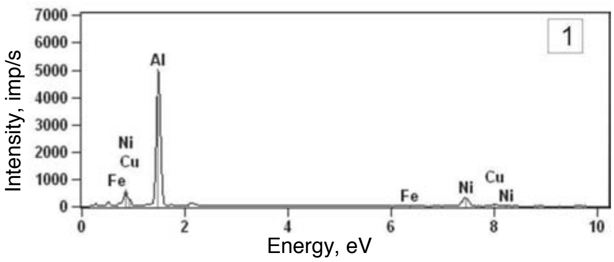


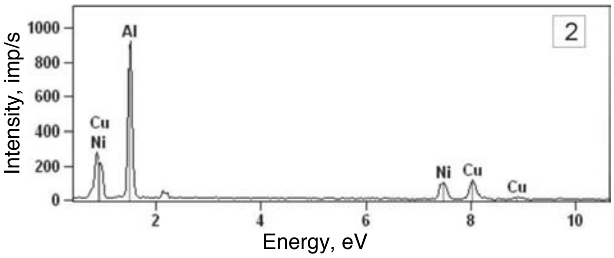
Fig. 2. Microstructure of AlCu4Ni2Mg alloy in T6 condition – the intermetallic phases particles on the boundaries of dendrites of solid solution (SEM–SE/BSE)

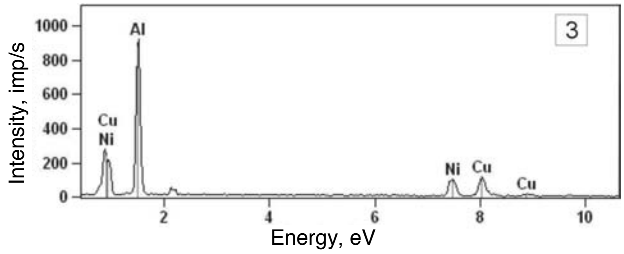
a)

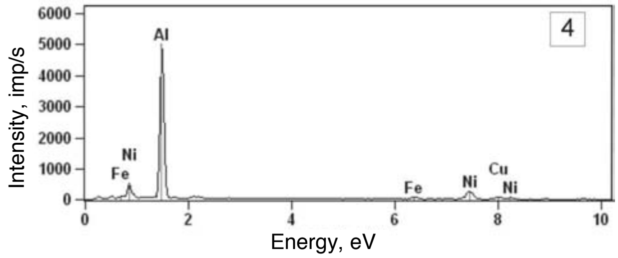


b)









c)

	Mg-K	Al-K	Fe-K	Ni-K	Cu-K
AlCu4Ni2Mg2 – pkt 1		76.32	5.95	13.39	4.35
AlCu4Ni2Mg2 – pkt2		47.26		23.27	29.48
AlCu4Ni2Mg2 – pkt 3		54.05		23.14	22.81
AlCu4Ni2Mg2 – pkt 4		85.32	3.18	9.08	2.43

Fig. 3. The particles of intermetallic phases in AlCu4Ni2Mg alloy: a) morphology, b) EDS spectra, c) chemical composition

3. Results and discussion

Figs. 1 and 2 show the microstructure of AlCu4Ni2Mg alloy (in T6 state) revealed by the optical and scanning microscopes observations.

The results of microscopic observations indicate that three types of inclusions are present in examined alloy:

- dispersed, spheroidal and strip shaped, distributed practically homogeneous in all volume of alloy (with slight concentration on the dendrite boundary areas),
- rounded, of developed surface, located on the dendrite boundary areas of solid solution *α*,
- ellipsoidal, located in the interdendritic regions of solid solution *α*.

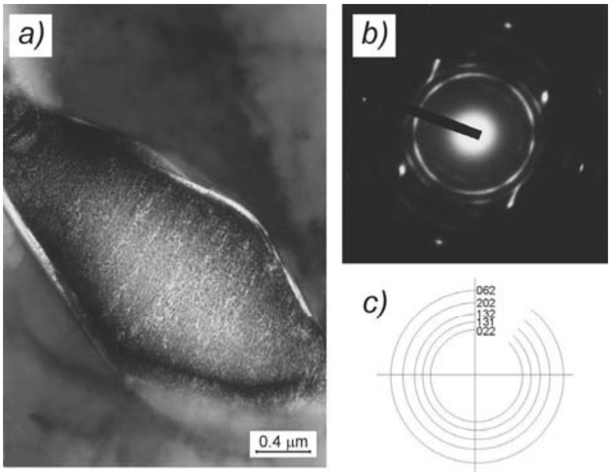
The EDS analysis revealed that rounded inclusions contain Al, Cu and Ni whereas elipsoidal one – Al, Fe, Ni and Cu (Fig. 3).

TEM micrographs and electron diffraction patterns analysis proved that the dispersed precipitates showed in Fig. 1 and 2 are particles of intermetallic phases S-Al_2CuMg (Figs. 4-5) and Al_6Fe (Fig. 6) besides the precipitates of hardening phase θ′-Al_2Cu were present in AlCu4Ni2Mg alloy (Fig. 7).

Microstructural examination of the AlCu4Ni2Mg alloy after soaking at 523 K temperature revealed that the long-term (from 100 to 750 h) exposure at high temperature did not affect the morphology and distribution of intermetallic phases (Fig. 8). Whereas significant increase of the particle size of hardening phase θ'-Al_2Cu with change in their shape was observed (Fig. 9).

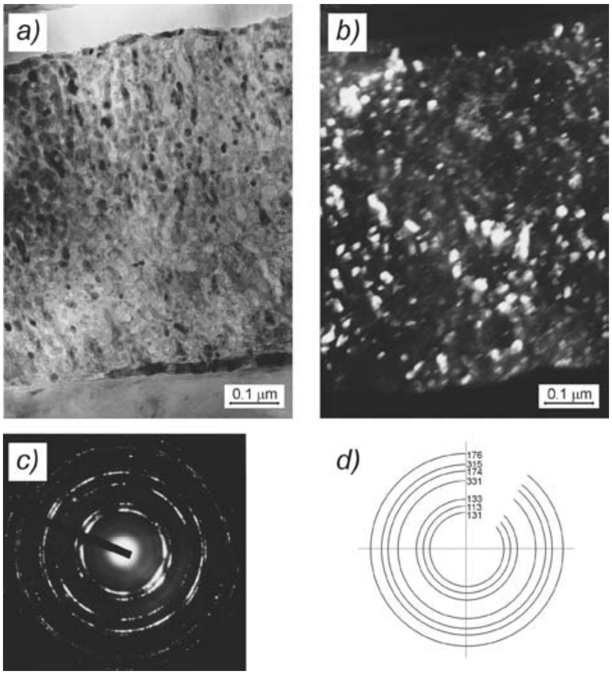
The mechanical properties of AlCu4Ni2Mg – yield stress $R_{0.2}$, tensile strength R_m and elongation A_5 – in T6 state and after soaking at 523 K are shown in Table 1 and Fig. 10.

It was found that the values of mechanical properties of alloy significantly decrease after long time exposure at elevated temperature. It was possible to calculate this tendency (in persentages) thanks to equation: $[(R-R_{(523)}) \times R^{-1}] \times 100\%$ (where R is $R_{0.2}$ or R_m value of alloy in T6 state, $R_{(523)}$ – $R_{0.2}$ or R_m after soaking at 523 K temperature) – Table 2. The $[(R-R_{(523)}) \times R^{-1}]$ equation presented as relationship with time of soaking permitted to estimate the stability of mechanical properties of alloy (Fig.11).



h k l	022	131	132	202	062
d (nm)	28.73	23.50	20.24	17.34	14.12
d (nm): *S-Al-Cu-Mg*	28.29	13.13	20.18	17.49	14.16

Fig. 4. Microstructure of AlCu4Ni2Mg alloy in T6 conditions (TEM): a) the precipitate of the S-Al_2CuMg phase, b) diffraction pattern, c) solution of diffraction pattern



h k l	131	113	133	331	174	315	176
d (nm)	22.86	19.77	17.07	12.06	10.25	9.83	8.53
d (nm):S-Al-Cu-Mg	23.12	20.00	17.06	12.09	10.27	9.71	8.64

Fig. 5. The particle of S-Al_2CuMg phase (TEM): a) bright field image, b) dark field image, c) diffraction pattern, d) solution of diffraction pattern

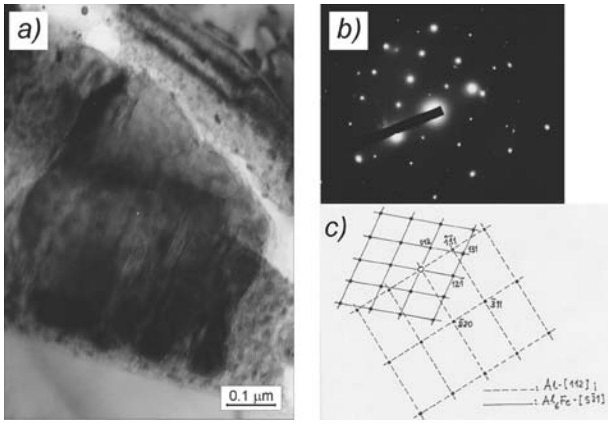
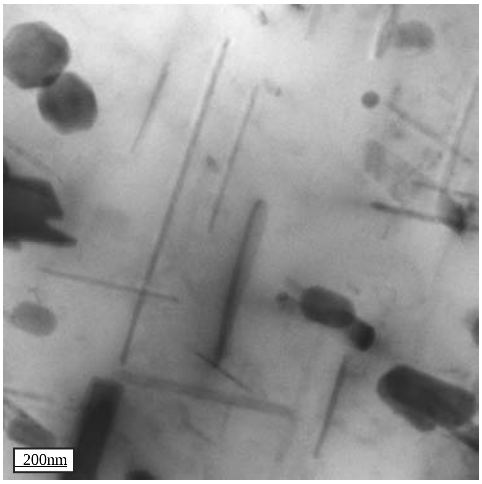


Fig. 6. Microstructure of AlCu4Ni2Mg alloy in T6 condition (TEM): a) the precipitate of the Al_6Fe phase, b) diffraction pattern, c) solution of diffraction pattern

a)



b)

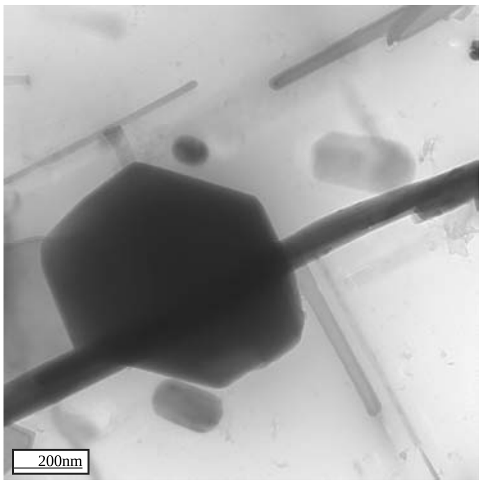


Fig. 7. Microstructure of AlCu4Ni2Mg alloy in T6 condition (TEM). The hardening phase θ'-Al_2Cu precipitates: a) strip-shaped, b) compact-shaped, visible as spheroidal on Figs. 1 and 2

a)

b)

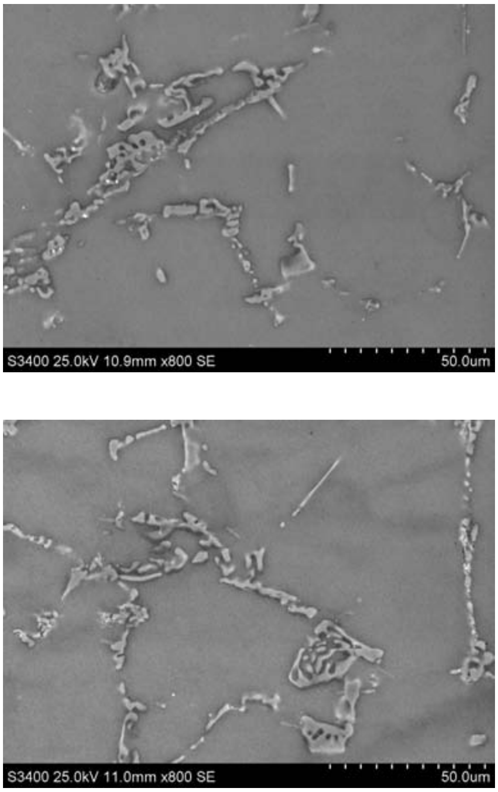


Fig. 8. The intermetallic phases particles in AlCu4Ni2Mg alloy after soaking at 523 K temperature at time: a) 100 h, b) 750 h

Table 1.
The mechanical properties of AlCu4Ni2Mg alloy in T6 state and after long-term soaking at 523 K temperature

Mechanical properties	In T6 state	After annealing at 523 K temperature				
		100 h			100 h	
$R_{e0.2}$, MPa	343	275	261	248	236	223
R_m, MPa	387	339	321	315	310	308
A_5, %	2.5	3.0	3.1	3.1	4.7	6.7

Table 2.
Change of yield stress $R_{e0.2}$ and tensile strength R_m of AlCu4Ni2Mg alloy after annealing at 523 K temperature

Annealing time at 523 K, h	$[(R- R_{(523)}) \times R^{-1}] \times 100$, %	
	$R = R_{e0.2}$	$R = R_m$
0	0	0
100	31	28
150	37	32
300	40	34
500	46	40
750	50	42

a)

b)

c)

d)

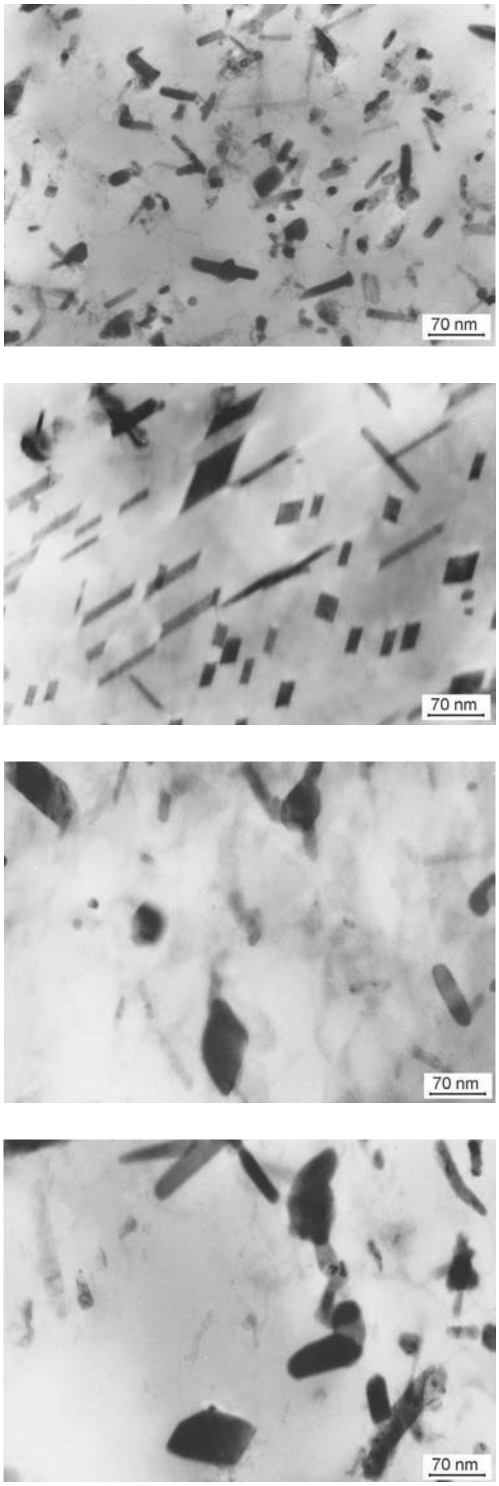


Fig. 9. Microstructure of AlCu4Ni2Mg alloy (TEM) – hardening phase θ'-Al_2Cu precipitates after soaking at 523 K temperature at time a) 100 h, b) 300 h, c) 500 h, c) 750 h

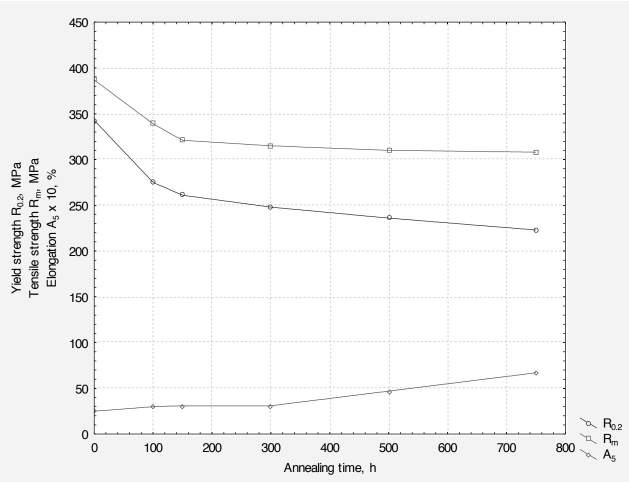


Fig. 10. Yield stress $R_{0.2}$, tensile strength R_m and elongation A_5 of AlCu4Ni2Mg alloy as a function of annealing time at 523 K temperature

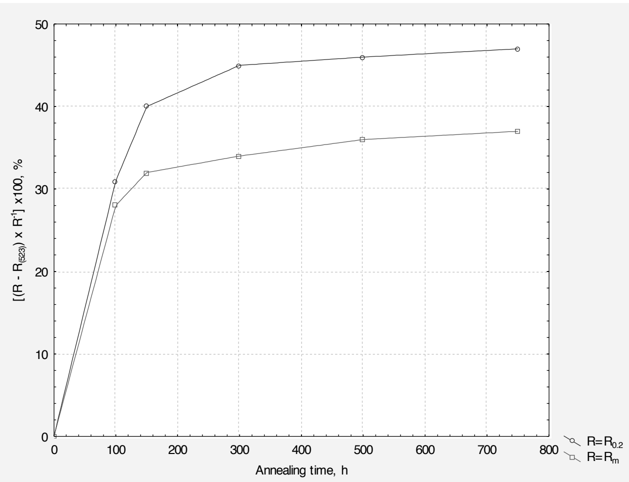


Fig. 11. Variation of values of yield stress $R_{0.2}$ and tensile strength R_m of AlCu4Ni2Mg alloy as a function of annealing time at 523 K temperature

The analysis of findings (Tables 1-2 and Figs. 10-11) showed that AlCu4Ni2Mg alloy is characterized by good stability of mechanical properties after long-term exposure at elevated temperature – retains additionally relatively high values of strength.

The results of microscopic observation (Figs. 8-9) clearly indicate that the degradation of microstructure under the influence of long-term operating heat loads was consisted in growth of hardening phase precipitates and change of their shape. These phenomena caused a change of the mechanism of hardening phase precipitates and dislocations interaction and in consequence decrease in mechanical properties of the alloy [13-15].

4. Conclusions

1. It was found that the process of microstructure degradation proceeded in AlCu4Ni2Mg alloy under conditions of long-term heat load. This degradation consists in growth of hardening phase θ'-Al_2Cu precipitates and change of their shape.
2. The increase of hardening precipitates size and change of their shape proceed proportionally to soaking time and result in decrease of mechanical properties of tested alloy.
3. The AlCu4Ni2Mg alloy is characterized by good stability of mechanical properties under conditions of long lasted heat load and by this reason is particularly accepted material for production elements of aircraft engine and machine parts operating under conditions of elevated temperature (up to 472 K) and high stress.

Acknowledgements

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