Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 45
ISSUE 2
April
2011

The structure and mechanical properties of Al-Mg-Mn alloys shaped in the process of thermomechanical treatment

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Received 12.02.2011; published in revised form 01.04.2011

Properties

ABSTRACT

Purpose: The aim of research was to investigate the effect of heat treatment and low-temperature thermomechanical treatment (LTMT) on the structure and mechanical properties of Al-Mg-Mn alloys.

Design/methodology/approach: The range of researches included: performance of heat treatment and low-temperature thermomechanical treatment of AlMg1.5 and AlMg3.5Mn alloys, carry out of static tensile tests, measurements of hardness, metallographic observation (TEM) and fractography (SEM).

Findings: Analysis of the results allows to determine the effect of precipitation hardening and low-temperature thermomechanical treatment on the structure and mechanical properties of AlMg1.5 and AlMg3.5Mn alloys and to determine the effect on the topography of the specimens fracture after decohesion in tensile tests. Moreover, SEM researches allow to identity the chemical composition of precipitates in the structure of investigated alloys.

Practical implications: The obtained results may serve as a basis for optimization of the process of the material used as components of vessels.

Originality/value: The mechanical properties of the investigated aluminium alloys increase with the quantity of Mg, independently of their state and the parameters of heat treatment and low-temperature thermomechanical treatment. More refinement of precipitations, which affect the mechanical properties in ageing, ensured by LTMT compared with conventional heat treatment.

Keywords: Metals; Non-ferrous metals; Aluminium alloys; Heat treatment; Low-temperature thermomechanical treatment; LTMT

Reference to this paper should be given in the following way:
W. Ozgowicz, E. Kalinowska-Ozgowicz, A. Kowalski, K. Gołombek, The structure and mechanical properties of Al-Mg-Mn alloys shaped in the process of thermomechanical treatment, Journal of Achievements in Materials and Manufacturing Engineering 45/2 (2011) 148-156.

1. Introduction

The development of the industry of alloys of non-ferrous metals is due to the demand for such materials in many domains of technology. Aluminum alloys used in plastic working together with magnesium and manganese are characterized by a low density and high resistance to corrosion [1,2]. They also display good mechanical properties, weldability and susceptibility to deep drawing [3,4]. Therefore, they are applied in many facilities of the

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shipbuilding industry, in the construction of moderately loaded elements of aeroplanes and vehicles, as well as in the chemical and food industry, and also in building engineering [5-7].

Al-Mg alloys usually contain additives of Mn, Cr, Si and other metals. Small concentrations of Mg (0.2% to 0.6%) or Cr (0.1% to 0.2%) increase the tensile strength of these alloys, whereas Ti and V affect the refinement of crystal grain in castings. The mechanical properties of binary Al-Mg alloys depend on the concentration of magnesium. Their strength can be also increased by about 10-15% by means of cold-working. This involves, however, a distinct deterioration of their plastic properties and resistance to corrosion [8,9]. In order to achieve a high strength of Al-Mg alloys, without reducing their plastic properties, they can be subjected to low-temperature thermo-mechanical treatment (LTMT), which combines conventional precipitation hardening with cold plastic deformation. Optimal properties of the alloy are essentially attained by an adequate choice of the parameters of this process, particularly in the range of plastic deformation and precipitation hardening [10-15].

The aim of the paper is, therefore, to determine the influence of the parameters of low-temperature thermomechanical treatment on the structure and mechanical properties of selected kinds of Al-Mg-Mn wrought alloys and to compare the effects of such a treatment with the conventional precipitation hardening of these alloys.

2. Experimental procedure

The investigations were carried out on the sheets of aluminum wrought alloys types AlMg1.5 and AlMg3.5Mn from industrial melting. The chemical composition of the investigated alloys is to be seen in Table 1, and their mechanical properties in delivered state in Table 2.

The alloy were subjected to low-temperature thermo-mechanical treatment comprising in the following operations: supersaturation, cold rolling and ageing in order to compare this treatment with the conventional heat treatment (CHT) in the range of supersaturation and ageing.

LTMT comprised the following operations:

- heating up to the temperature of supersaturation 550°C,
- soaking at this temperature for 8 hours,
- supersaturation in water from the soaking heat,
- cold plastic deformation by reduction rolling with a draft coefficient of about 36%, 56% and 74%,
- ageing at temperature of 200°C and 300°C for 8 hours, connected with air cooling.

Conventional heat treatment comprised the following operations:

- supersaturation in water from the temperature of 550°C, preceded by soaking for 8 hours,
- ageing at 200°C and 300°C for 8 hours with simultaneous air cooling.

The heating and soaking in the operation of supersaturation were carried out in an electrical chamber furnace with a nominal temperature of 1350°C, equipped with a thermocouple Pt-RhPt and a microprocessor control system, ensuring the upkeep of the temperature adjusted zonally with an accuracy of ±2°C. Ageing was achieved in an electric furnace with gap chamber and a working temperature of up to 600°C, equipped with a thermo-regulator ensuring measurements with an accuracy of ±1°C. In the case of LTMT the rolling was performed in a horizontal stand of the type Sir James FARMER NORTON with a force exerted on the rollers amounting to about 20 t. The parameters of the cold rolling process of the alloy sheets of the investigated alloys have been gathered in Table 3.

Controlling analyses of the chemical composition of the investigated alloys were carried out on the X-ray spectrometer ZSX Primus produced by the firm Rigaku. The mechanical properties of the alloys were determined basing on a static tensile test performed on the testing machine ZWICK/Z100 at a traverse speed of 2 mm/min. The analyses concerned the tensile strength R_m, the yield strength $R_{p0.2}$, the elongation A and the reduction of area at fracture Z. Metallographic tests were carried out on longitudinal metallographic specimens of the investigated alloys in the delivered state, after LTMT and CHT. The metallographic specimens were prepared by submerging the samples in epoxy resin, their grinding and mechanical polishing, followed by etching in a 2% aqueous solution of HF acid. The structures were scanned by means of a light-microscope Leica MEF 4A with a magnification of up to 1000 times. The hardness of the provided alloys and also after their LTMT and CHT was determined on the hardness testing

Table 1.
Chemical composition of the investigated alloys

No.	Kind of the alloy	Concetration of the elements, % by weight								
		Mg	Mn	Si	Zn	Fe	Ti	Cu	Cr	Al
1.	AlMg1.5	1.39	0.28	0.19	-	0.16	-	0.09	-	rest
2.	AlMg3.5Mn	3.71	0.59	0.23	0.02	0.20	0.01	0.07	0.06	rest

Table 2.
Mechanical properties of the investigated alloys in the delivered state

No.	Kind of the alloy	Mechanical properties				
		$\overline{R_m}$ [MPa]	$\overline{R_{p0,2}}$ [MPa]	$\overline{A}$ [%]	$\overline{Z}$ [%]	Hardness # $\overline{HV50}$
1.	AlMg1.5	182.0	89.5	22.3	55.2	60.5
2.	AlMg3.5Mn	324.4	177.9	22.9	39.8	83.3

Table 3.
Diagram of cold rolling of the alloy sheets in the case of LTMT

No.	Kind of alloy	Denotation of the band	No. of the roll pass 0	1	2	3	4	5	Degree of reduction [%]
			Sheet thickness [mm]						
1.	AlMg1.5	1	9.80	7.00	4.00	2.85	-	-	70.9
2.	AlMg3.5Mn	5.1.1	12.30	10.60	9.25	7.85	-	-	36.0
		5.1.2	12.30	10.60	9.25	7.85	5.37	-	56.0
		5.1.3	12.30	10.60	9.25	7.85	5.37	3.20	74.0

machine HAUSER making use of the Vickers method at a load of 50 N. The micro-hardness of the matrix and precipitations of the investigated alloys were tested on the hardness testing machine PMT3, applying a load of 5 g, the duration of the measurements amounting to 10 seconds.

Fractographic tests of fractures after the decohesion of the samples in the tensile test and observations of metallographic specimens were performed in a scanning electron microscope (SEM) from the firm ZEISS SUPRA 25 with the electronic gun GEMINI applying a voltage of 20 kV and a magnification of up to $5{\cdot}10^3$x. The chemical composition of the precipitations detected on the metallographic specimens and fractures were determined by means of X-ray microanalysis applying the attachment EDAX.

X-ray examination were carried out on an X-ray diffractometer XRD7 produced by the firm Seifert-FPM, making use of the characteristic radiation of the anode CoK_α, filtered by means of iron. The qualitative phase analysis was contained within the angular range 2θ from 20° to 100°, corresponding to range of the interplane distances d_{hkl} from 0.5155 to 0.1168 nm. In the investigations discrete method was used applying a measurement step of Δθ 0,04° in the scale 2θ and the counting time the number of impulses in the point – 3 sec.

3. Results and discussion

Basing on metallographic observations it has been found that the structure of the supplied sheets of the AlMg1.5 and AlMg3.5Mn alloys consists of the matrix α and intermetallic phases of various sizes. The phases are arranged in chains along the direction of rolling (Fig. 1) or occur in clusters (Fig. 2). The size of precipitations arranged in chains in the AlMg1.5 alloy amounts to 1-10 μm. In the matrix of the AlMg3.5Mn alloy besides linearly arranged precipitations also polygons phases were detected, whose size amounted to up to 20 μm (Fig. 2).

After supersaturation from 550°C the structure of the investigated alloys (Figs. 3-6) revealed grains of the solution α with irregular boundaries with precipitations arranged in chains, displaying a hardness of 192 HV (Fig. 6). Besides linearly arranged precipitations, the AlMg3.5Mn alloy displays intermetallic dispersive phases all over the observed surface. Their presence in the structure of supersaturated alloys may prove their complex construction and primeval character, determined by precipitation in the process of crystallization [5]. The microhardness of the area surrounding the matrix after supersaturation amounts in the case of the AlMg1.5 alloy to about 45 HV, and in the case of the AlMg3.5Mn alloy to about 58 HV. The difference of the hardness is due to the varying degree of the consolidation of the solution of the alloys.

The structure of the AlMg1.5 and AlMg3.5Mn alloys after precipitation hardening connected with ageing at 200°C and 300°C does not display any considerable differences in comparison with their structure after supersaturation (Figs. 7, 8). In the matrix of the solution α of the investigated alloys occur linearly arranged precipitations of intermetallic phases.

In result of rolling in LTMT the intermetallic phases occurring in the structure of cold-deform alloys were partly crushed and comminuted (Figs. 9, 10). After deformation with a draft coefficient of about 70%, the structure of the AlMg1.5 alloy contains precipitations in the form of polygons and spheroids either in clusters or in linear arrangement, their size reaching up to 7 μm, they may also be distributed regularly dispersively in the solution α (Fig. 9). After deformation with a draft of about 74% the AlMg3.5Mn alloy is in the case of LTMT characterized by a similar state of precipitations. The precipitations clustered in the micro-areas of the matrix are, however, larger, reaching up to 10 μm (Fig. 10).

After ageing at a temperature of 200°C in LTMT the investigated alloys display a structure of deformed grains of the matrix α with precipitations (Fig. 11), whereas after ageing at 300°C a partially recrystallized structure of the matrix α has been found in the AlMg3.5Mn alloy, with precipitations of intermetallic phases (Fig. 12). Besides linearly arranged precipitations in the structure of these alloys also minute spherical dense phases have been detected, regularly distributed in the matrix α (Figs. 11, 12). Metallographic investigations have made it possible to state that larger comminutes of precipitations in the matrix of the solution α affecting the mechanical properties attained in the course of ageing are ensured by LTMT than CHT.

Investigation of metallographic specimens of the AlMg3.5Mn alloy in SEM revealed after LTMT the occurrence of precipitation of various morphologies and phase contrast. A microanalysis of the chemical composition has shown that light-etching precipitations indicate the presence of Al, Mg, Mn, Si and Fe (Fig. 13), whereas contrasting precipitations contain Al, Mg and Si (Fig. 14). The concentration of the alloy elements in light precipitations, tested by means of a beam of reversely diffused electron, indicate that they may probably be phases of the $Al_6(Mn, Fe)$, $AlMg_2Mn$ and AlFeSi type (Fig. 13) or in precipitations with a dark contrast of the Mg_2Si type (Fig. 14). The presence of the Al_3Mg_2 type in the structure of the AlMg1.5 and AlMg3.5Mn alloys after LTMT and CHT has been confirmed by the results of X-ray examination. Diffraction patterns of the AlMg3.5Mn alloy after these treatments display diffraction lines resulting from the planes of the solution α and the Al_3Mg_2 phase (Figs. 15, 16).

The results of fractographic investigation permit to assess the character of the fracture as well as the morphology of the precipitations of the AlMg1.5 and AlMg3.5Mn alloys after LTMT and in delivered state (Figs. 17, 18). Irrespective of the applied treatment, the investigated alloys are characterized by a ductile transcrystalline fracture with characteristic craters of various sizes and with abundant precipitations. The precipitation, situated mainly at the bottom of the craters, are covered with cracks and fragmented. Smooth planes of the fragmented phases prove their brittle cracking (Figs. 17, 18). An X-ray microanalysis of the observed precipitations distinguished in the AlMg3.5Mn alloy two kinds of precipitations containing mainly Mn and Fe, as well as Mg and Si. Probably these are precipitations of the secondary solid solution of the Al_6(Mn, Fe) type and the Mg_2Si phase, as also suggested by the author of [5].

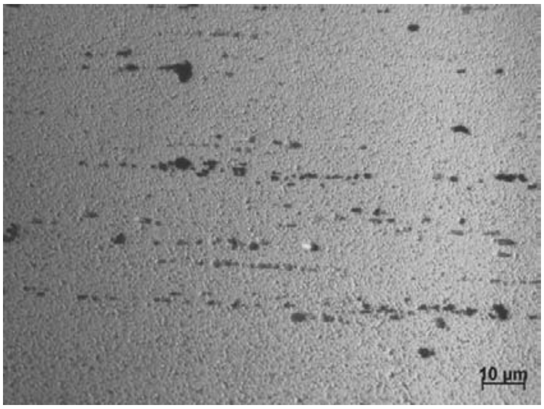


Fig. 1. Fine precipitations, linearly arranged in the matrix - α. AlMg1.5 alloy – delivered state

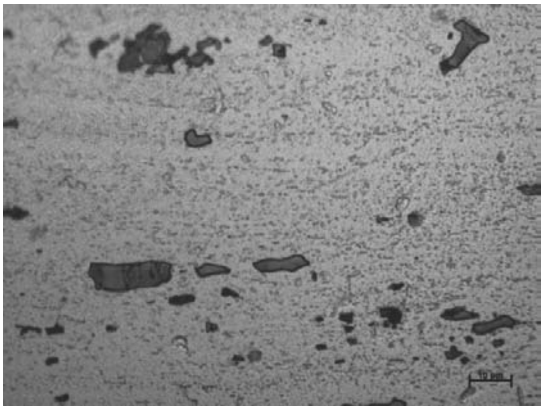


Fig. 2. Precipitations in the matrix -α. AlMg3.5Mn alloy – delivered state

Fig. 3. Matrix - α with fine precipitations. AlMg1.5 alloy after supersaturation

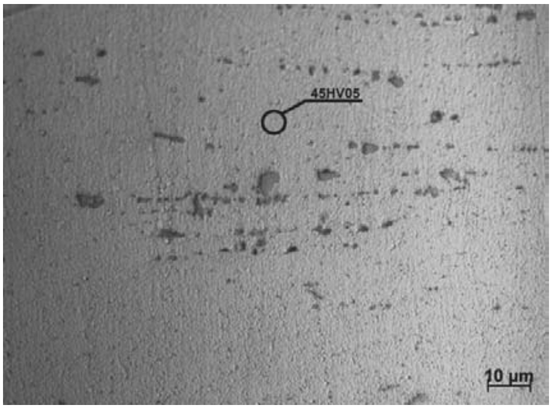


Fig. 4. Precipitations in the matrix -α. AlMg1.5 alloy after supersaturation. Magnification of Fig. 3.

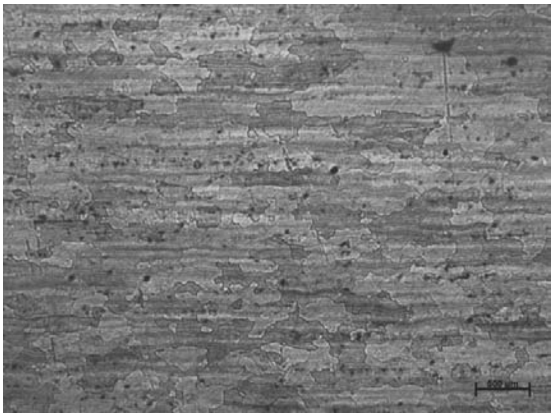


Fig. 5. Grains of the α- solution with precipitations. AlMg3.5Mn alloy after supersaturation

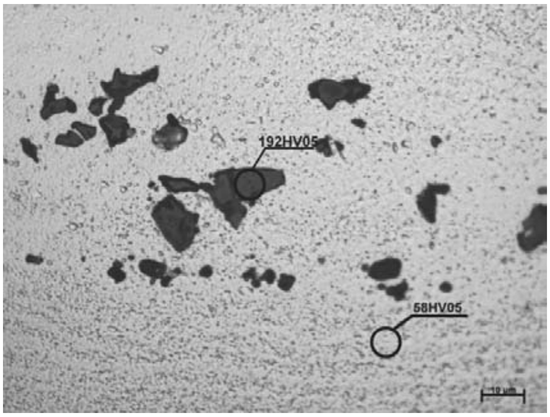


Fig. 6. Precipitations in the matrix -α. AlMg3.5Mn alloy after supersaturation. Magnification of Fig. 5

Fig. 7. Grains of the α - solution with precipitations arranged in bands. AlMg1.5 alloy after CHT, ageing at 200°°C

Fig. 8. Single precipitations arranged in bands in the matrix -α. AlMg3.5Mn alloy after CHT, ageing at 200°C

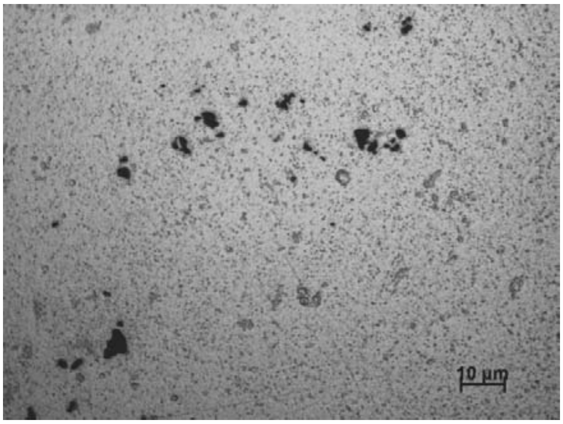


Fig. 9. Fine precipitations in the matrix -α. AlMg1.5 alloy after rolling (z=70%), LTMT

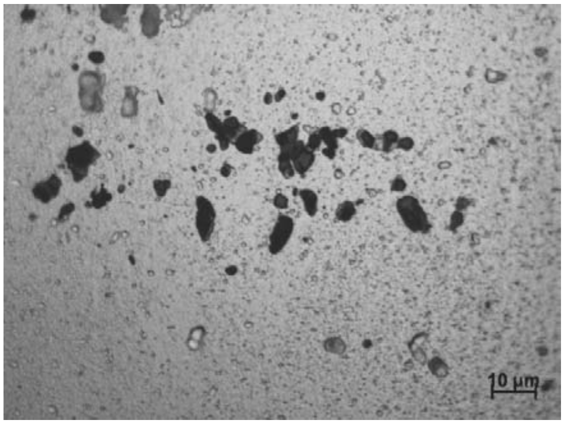


Fig. 10. Precipitations in the matrix -α. AlMg3.5Mn alloy after rolling (z=74%), LTMT

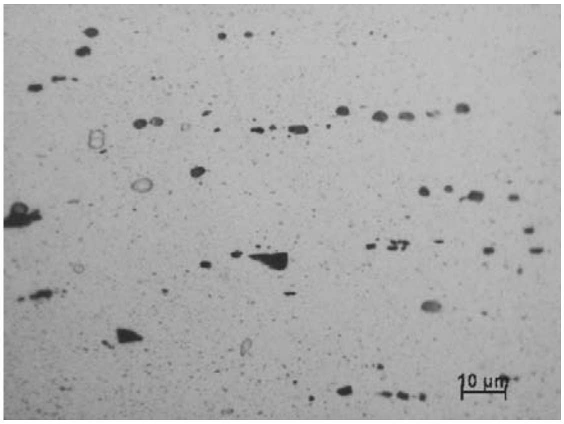


Fig. 11. Fine precipitations arranged in the matrix -α in bands. AlMg1.5 alloy, LTMT, ageing at 200°C

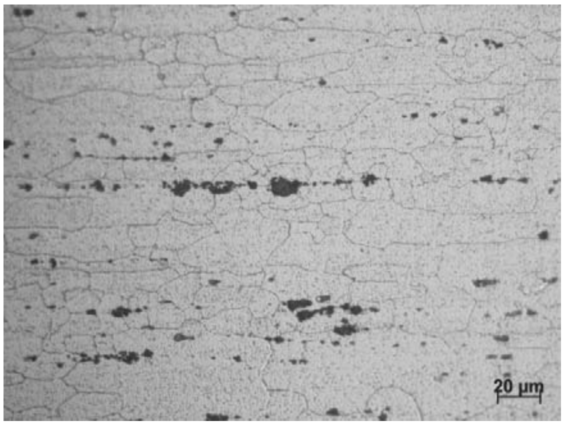


Fig. 12. Fine precipitations in the matrix -α. AlMg3.5Mn alloy, LTMT, ageing at 300°C

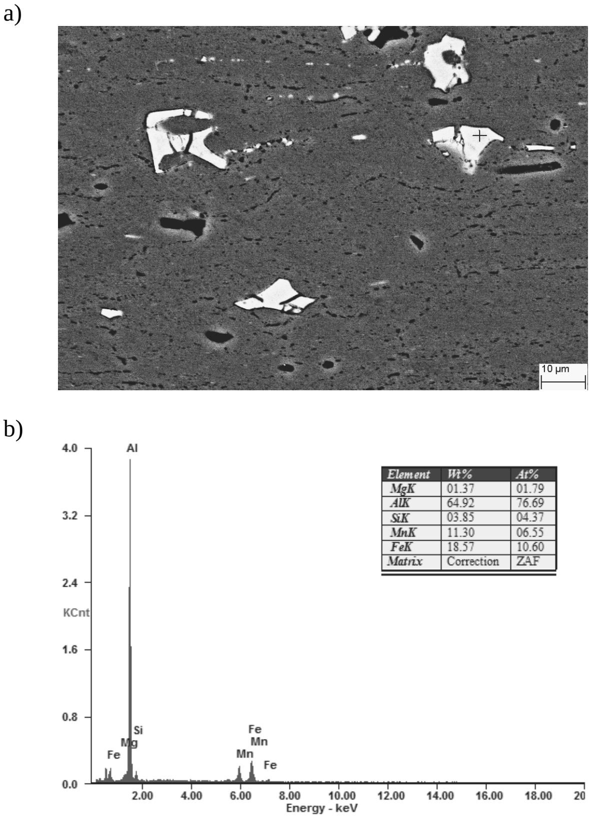


Fig. 13. Precipitations in the AlMg3.5Mn alloy in delivered state: a) SEM, b) X-ray microanalysis of light precipitations

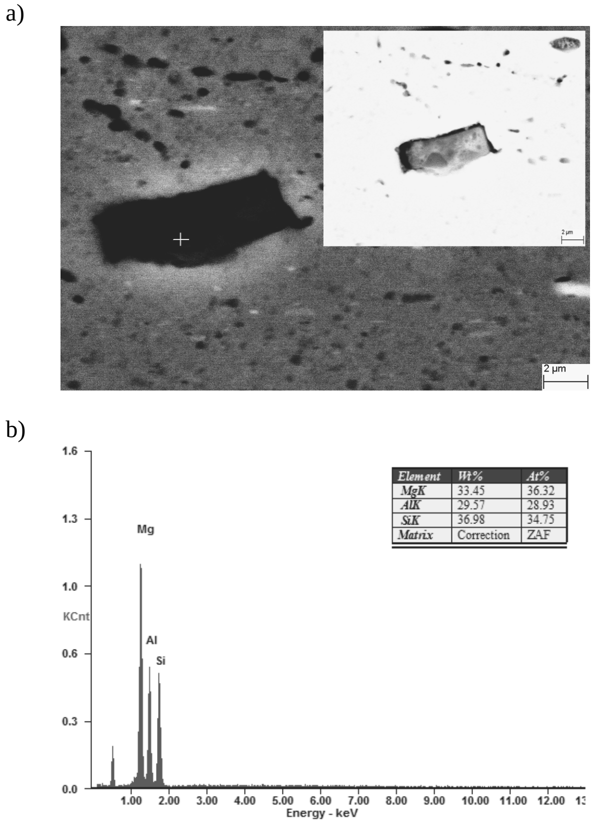


Fig. 14. Precipitations in the AlMg3.5Mn alloy in delivered state: a) SEM, b) X-ray microanalysis of dark precipitations

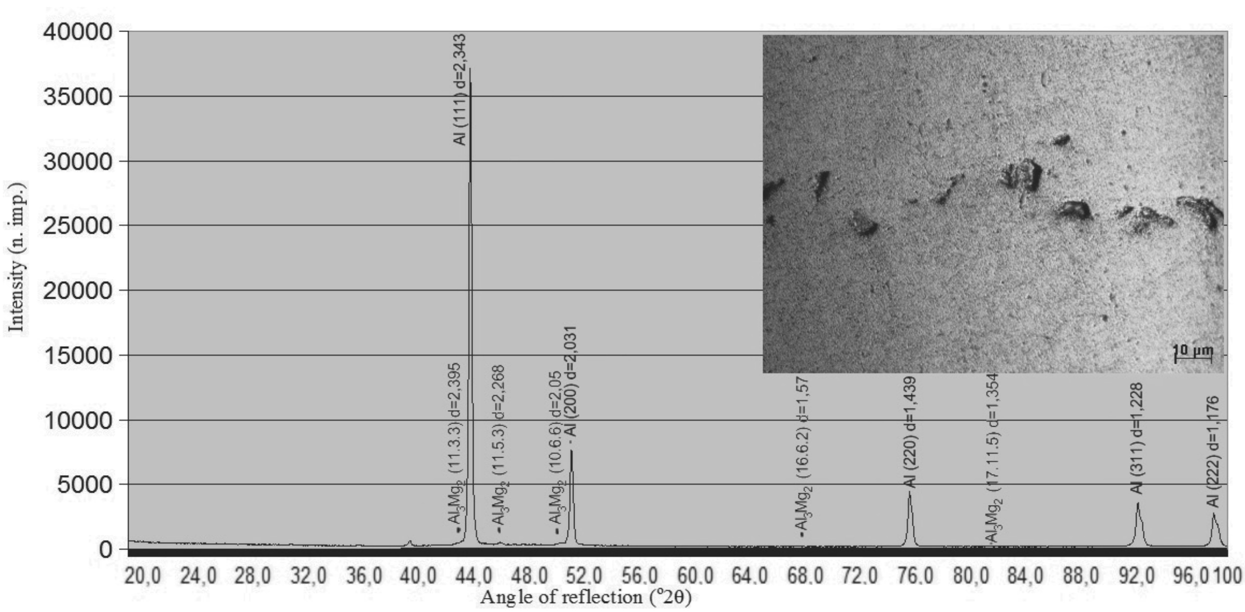


Fig. 15. Diffraction pattern of the AlMg3.5Mn alloy after CHT

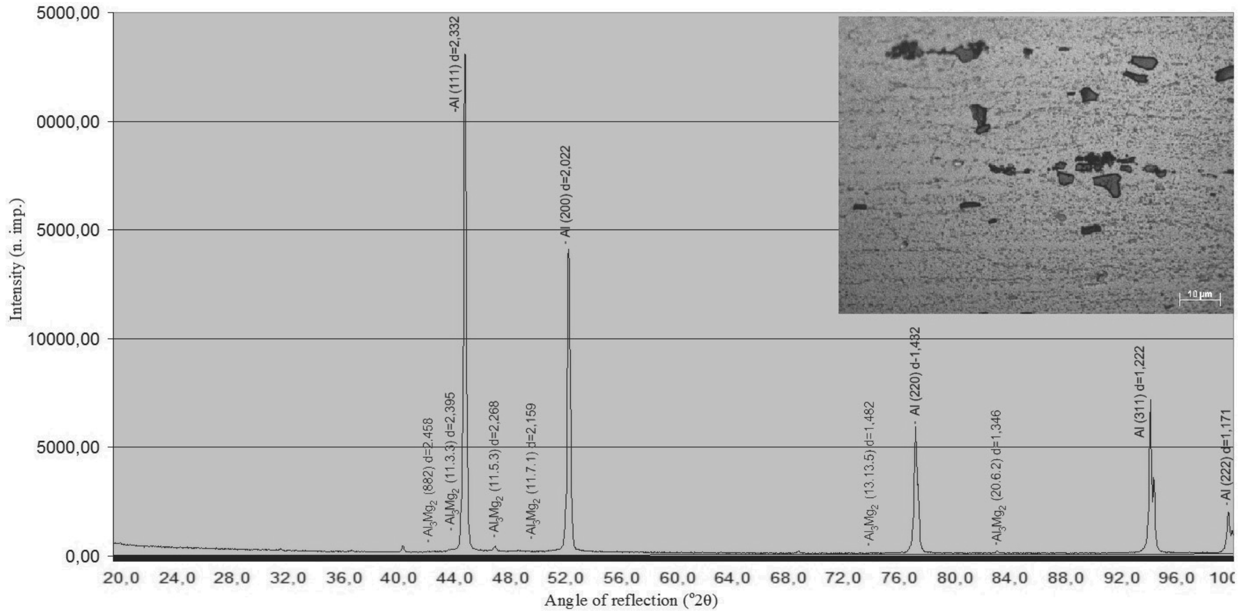
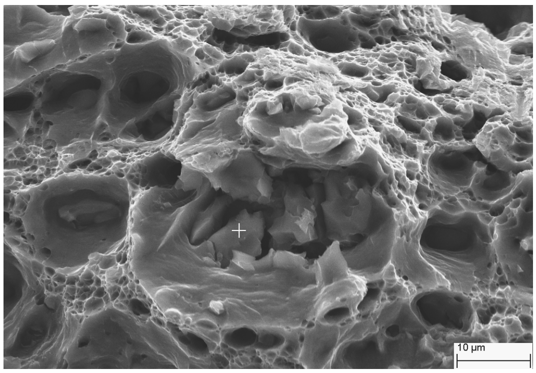
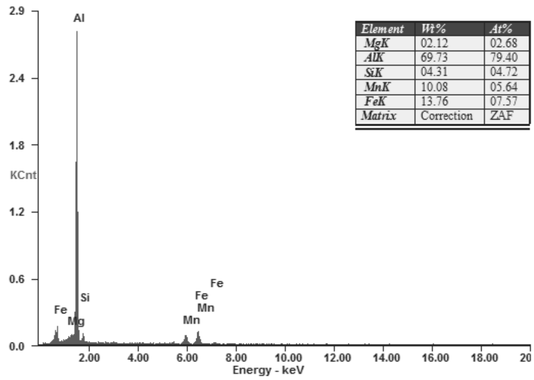


Fig. 16. Diffraction pattern of the AlMg3.5Mn after LTMT

a)



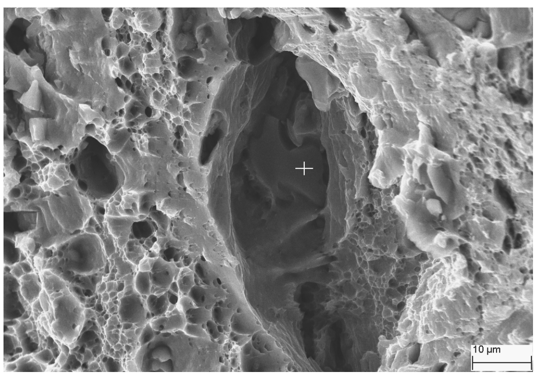
b)



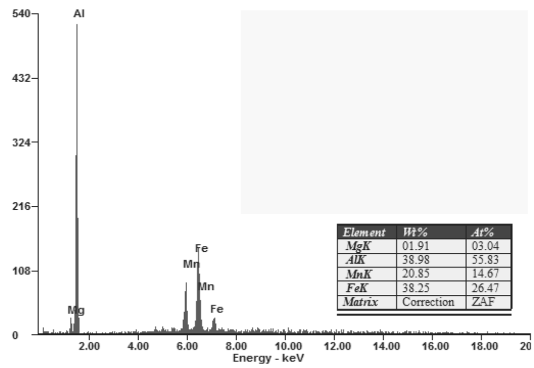
Element	Wt%	At%
MgK	02.12	02.68
AlK	69.73	79.40
SiK	04.31	04.72
MnK	10.08	05.64
FeK	13.76	07.57
Matrix	Correction	ZAF

Fig. 17. Ductile fracture with precipitations at the bottom of the craters in the AlMg3.5Mn alloy after LTMT (a), results of the microanalysis of the chemical composition of the precipitation (b)

a)



b)



Element	Wt%	At%
MgK	01.91	03.04
AlK	38.98	55.83
MnK	20.85	14.67
FeK	38.25	26.47
Matrix	Correction	ZAF

Fig. 18. Fragmented precipitation at the bottom of the craters in the AlMg3.5Mn alloy after in delivered state (a), results of the microanalysis of the chemical composition of the precipitation (b)

The investigations dealt with in the present paper prove the possibility of shaping the structure and attaining better properties of the strength of the Al-Mg and Al-Mg-Mn alloys by means of LTMT which combines operations of plastic deformation and precipitation hardening.

The AlMg1.5 and AlMg3.5Mn alloys subjected to CHT display a various hardness already after their supersaturation, due to the various supersaturation of the solution α with the alloying elements, particularly Mg and Mn (Table 4, Fig. 19). The values expressing the elongation of the investigated alloys are similar (A about 30%), whereas the maximum reduction of area (Z about 69%) occurs in the AlMg1.5 alloy. Ageing at a temperature of 300°C for 8 hours deteriorates the strength properties by about 10% at a simultaneous slight increase or upkeep of the plastic properties (Fig. 19). The AlMg3.5Mn alloy, aged at a temperature of 300°C, displays comparable values of A and Z as in the saturated state. The analysis of the mechanical properties permits to ascertain that CHT of the investigated alloys, though practicably possible, is less effective, which has also been confirmed by the author of [5].

Of essential importance, concerning the improvement of the mechanical properties of Al-Mg-Mn alloys, is the application of LTMT. Precipitation hardening combined with cold rolling increases their strength, deteriorating the plastic properties of the AlMg1.5 and AlMg3.5Mn alloys (Table 5, Fig. 20). The best strength of the AlMg1.5 alloy, viz. R_m about 297 MPa, $R_{p0.2}$ about 260 MPa, A about 5%, Z about 26% and hardness HV about 90, was achieved after LTMT, comprising supersaturation in water from the temperature 550°C, deformation by cold rolling with a draft coefficient z ≈ 70% and ageing for 8 hours at 200°C connected with air cooling. In the case of applying this treatment a more favourable increase of strength was effected in the AlMg3.5Mn alloy, due to the higher concentration of Mg and Mn in this alloy. The strength of the AlMg1.5 alloy was after its LTMT connected with ageing at 200°C is markedly higher than after its CHT: R_m by about 110 MPa, $R_{p0.2}$ by about150 MPa, and the reduced values of A and Z amounted 5.2% and 26.1%, respectively (Table 5). Ageing of the AlMg1.5 alloy at 300°C permits in the case of LTMT to obtain more favourable plastic properties: A about 20% and Z about 51%, the strength being somewhat lower: R_m about 197 MPa, $R_{p0.2}$ about 85 MPa. The AlMg3.5Mn alloy after cold rolling in the LTMT attains its maximum mechanical properties, amounting to R_m=422.5 MPa and $R_{p0.2}$=389.8 MPa. Ageing of this alloy at a temperature of 200°C and 300°C results in a deterioration of its strength and hardness and an increase of its plasticity, mainly due to the process of recrystallization of the matrix in the course of ageing (Fig. 12). After LTMT the AlMg3.5Mn alloy displays higher values of R_m by about 36 MPa and $R_{p0.2}$ by about 40 MPa, and also a higher hardness by about 30 HV, going together with a shorter elongation by about 10% and a reduction of area by about 5%, if compared with the state after CHT (Tables 4 and 5, Figures 19, 20).

Basing on metallographic investigations and strength tests we may say that the performed operations of the heat treatment and thermomechanical treatment do not indicate any distinct changes in the structure and mechanical properties of the investigated alloys if compared with the delivered state, which proves indirectly that the delivered investigated material results from a production process realizing similar technologies of thermo-mechanical treatment. It could also be observed that the content of magnesium influences the mechanical properties of the investigated alloys – an increased content of Mg generally resulted in an increase of their strength and a smaller reduction of area, the values of elongation remaining comparable. LTMT with ageing at a temperature of 200°C affects a rise of the strength of the AlMg3.5Mn alloy, particularly of the yield strength $R_{p0.2}$. An increase of the temperature of ageing within the range of 200-300°C, however, leads to decreased values of R_m and $R_{p0.2}$, both in the case of heat treatment and thermomechanical treatment.

Table 4.
Mechanical properties of the investigated alloys after CHT

Kind of the alloy	Precipitation hardening														
	Supersaturation Temp. 550°C/8h					Ageing									
						Temp. 200°C/8h					Temp. 300°C/8h				
	$\overline{R_m}$ [MPa]	$\overline{R_{p0,2}}$ [MPa]	$\overline{A}$ [%]	$\overline{Z}$ [%]	$\overline{HV50}$	$\overline{R_m}$ [MPa]	$\overline{R_{p0,2}}$ [MPa]	$\overline{A}$ [%]	$\overline{Z}$ [%]	$\overline{HV50}$	$\overline{R_m}$ [MPa]	$\overline{R_{p0,2}}$ [MPa]	$\overline{A}$ [%]	$\overline{Z}$ [%]	$\overline{HV50}$
AlMg1.5	189.4	111.7	28.6	59.4	52.1	190.7	111.5	30.8	68.6	66.0	179.3	85.6	31.4	67.2	68.8
AlMg3.5Mn	294.6	128.7	32.1	42.4	81.4	281.8	121.7	33.1	41.0	78.1	270.5	117.1	32.8	37.2	83.5

Table 5.
Mechanical properties of the investigated alloys after LTMT

Kind of the alloy	Draft coeff. [%]	Cold rolling					Ageing									
							Temp. 200°C/8h					Temp. 300°C/8h				
		$\overline{R_m}$ [MPa]	$\overline{R_{p0,2}}$ [MPa]	$\overline{A}$ [%]	$\overline{Z}$ [%]	$\overline{HV50}$	$\overline{R_m}$ [MPa]	$\overline{R_{p0,2}}$ [MPa]	$\overline{A}$ [%]	$\overline{Z}$ [%]	$\overline{HV50}$	$\overline{R_m}$ [MPa]	$\overline{R_{p0,2}}$ [MPa]	$\overline{A}$ [%]	$\overline{Z}$ [%]	$\overline{HV50}$
AlMg1.5	70.9	281.9	277.6	1.4	25.1	104.4	296.8	260.2	5.2	26.1	88,6	197.2	84.7	20.4	50.8	79.8
AlMg3.5Mn	36.0	375.7	334.7	9.6	15.0	121.3	350.1	264.1	15.7	23.4	119.0	309.5	152.2	27.0	33.2	83.0
	56.0	408.1	374.6	6.6	11.2	125.7	378.6	298.2	13.4	18.3	116.1	303.3	150.3	22.1	36.3	81.4
	74.0	422.5	389.8	2.9	17.4	131.1	390.4	321.7	7.4	14.6	139.7	306.4	158.1	22.1	32.8	113.4

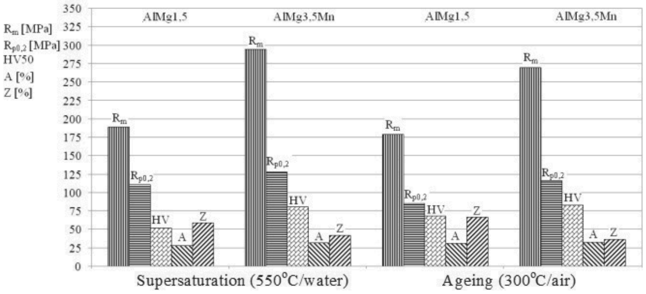


Fig. 19. The effect of CHT on the mechanical properties of the AlMg1.5 and AlMg3.5Mn alloys

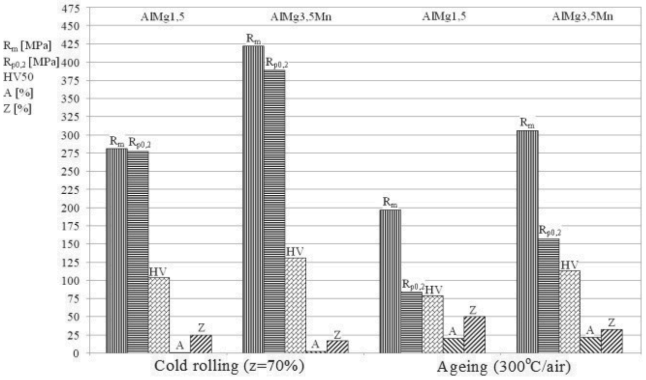


Fig. 20. The effect of LTMT on the mechanical properties of the AlMg1.5 and AlMg3.5Mn alloys

4. Conclusions

1. The application of the thermomechanical and conventional heat treatment involves a considerable refinement of structure and also a modification of the precipitations of the AlMg1.5 and AlMg3.5Mn alloys, determining their mechanical properties, without eliminating the primary phases in the solution α which had been formed in the course of the crystallization of the investigated alloys.
2. LTMT increases the strength (R_m, $R_{p0.2}$ and HV) of the investigated alloys, displaying satisfactory plastic properties (A and Z), if compared with CHT.
3. The best strength (R_m about 390 MPa, $R_{p0.2}$ about 322 MPa and HV about 140) have been attained in the AlMg3.5Mn alloy after LTMT, comprising the following operations: supersaturation from the 550°C, cold rolling with a draft coefficient of about 70% and ageing at a temperature of 200°C.
4. The strain hardening of the investigated alloys is determined both by the mechanism of solution hardening and by the precipitation of the phases identified by X-ray examination as Mg_2Si and $Al_6(Mn, Fe)$.
5. The rise of the temperature in the course of ageing leads in the case of LTMT to a distinct increase of the plastic properties of the investigated alloys, particularly a larger percentage reduction of area at fracture.
6. Both in the case LTMT and CHT the investigated alloys display ductile transcrystalline fractures, including numerous precipitations of secondary phases.

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