Archives of Materials Science and Engineering

Volume 28
Issue 9
September 2007
Pages 533-540

International Scientific Journal published monthly as the organ of the Committee of Materials Science of the Polish Academy of Sciences

The influence of age hardening on the microstructure of GA8 magnesium alloy

A. Kiełbus [a,*], J. Adamiec [a], J. Cwajna [a], J. Paśko [b]

[a] Department of Materials Science, Silesian University of Technology, ul. Krasińskiego 8, 40-019 Katowice, Poland

[b] ZM WSK Rzeszów S.A., ul. Hetmańska 8, 35-078 Rzeszów, Poland

* Corresponding author: E-mail address: andrzej.kielbus@polsl.pl

Received 20.02.2007; published in revised form 01.09.2007

ABSTRACT

Purpose: GA8 magnesium alloy is a general purpose gravity sand casting alloy containing aluminum, zinc and manganese. Typically, it is used in aerospace, automotive or commercial casting applications particularly where there is no high temperature requirement. Particularly for elements of the car interior, car body, chassis and driving gears. The aim of this paper is to present the results of investigations on the microstructure of the GA8 magnesium alloy after precipitation hardening.

Design/methodology/approach: The study was conducted on GA8 magnesium alloys in as-cast condition and after heat treatment. The microstructure was characterized by optical microscopy (Olympus GX-70) and a scanning electron microscopy (Hitachi S3400) equipped with an electron dispersive detector EDS (VOYAGER of NORAN INSTRUMENTS). To measure the stereological parameters, an image analysis program “AnalysisPro®” was used.

Findings: A cast of the GA8 magnesium alloy shows the presence of continuous and discontinuous precipitates of β ($Mg17Al12$) phase at the solid-solution grain boundaries, Moreover, the occurrence of $Mg2Si$ and $Mn5Al8$ phases has been provided. After solution treatment at 415°C the area fraction of continuous and discontinuous β phase precipitates decreased. After ageing at 170°C GA8 alloy is characterized by discontinuous β phase along the solid solution grain boundaries. Area fraction of this phase increased compared to supersaturated state.

Research limitations/implications: Future researches should involve investigations of the influence of precipitation hardening parameters on the mechanical properties of GA8 magnesium alloy.

Practical implications: The established precipitation hardening parameters can be useful for preparing heat treatment technology of the GA8 magnesium alloy.

Originality/value: The relationship between the as cast structure, precipitation hardening parameters and $Mg17Al12$ phase morphology in GA8 magnesium alloy was specified.

Keywords: Metallic alloys; Heat treatment; GA8 magnesium alloy

MATERIALS

1. Introduction

Magnesium alloys apart from aluminium alloys belong to the lightest constructional materials. They are characterised by good mechanical properties, corrosion resistance and good castability. Therefore they find widespread application in the automotive and aircraft industries, particularly for elements of the car interior, car body, chassis and driving gears [1-3]. The basic magnesium alloys contain manganese, aluminium and zinc which allow obtaining suitable properties. Manganese does not nave much effect on tensile strength, however, it does increase yield strength slightly. Its most important function is to improve the saltwater resistance of Mg-Al alloys by removing iron and other heavy metal elements into relatively harmless intermetallic compounds.

The quantity of manganese in magnesium alloys is limited by its relatively low solubility in magnesium. Manganese content in alloys with an Al addition does not exceed 0.3% and 1.5% in alloys without Al addition. Aluminium enhances both tensile strength and hardness, and improves casting properties of an alloy. The best ratio of mechanical to plastic properties is obtained with a 6% Al content. Magnesium and aluminium are fully soluble in the liquid state and a eutectic reaction takes place at 437°C: liquid → α(Mg) + β($Mg_{17}Al_{12}$). According to the phase diagram (Fig.1) the aluminium contents of the various phases present at the eutectic temperature 437°C are approximately 33wt% (eutectic α+β), 41wt.% (β phase) and 12,7 wt.% (α phase). An addition of zinc in combination with Al aims at improving tensile strength at a room temperature, however 1% of Zn with a 7÷10% Al content in an alloy enhances hot cracking [4-6].

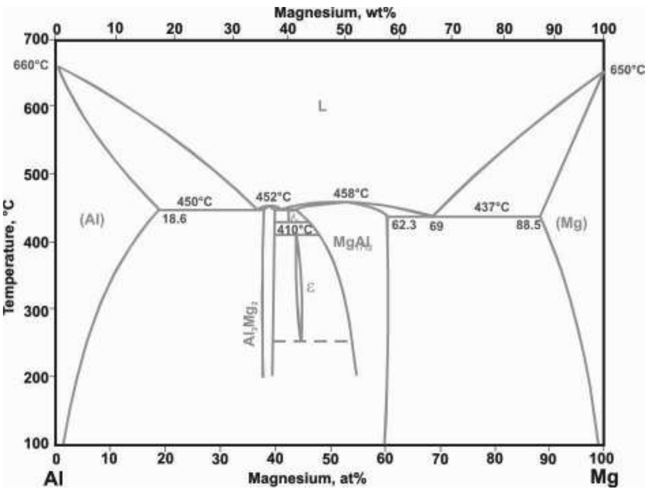


Fig. 1. Mg-Al binary phase diagram [4]

In the microstructure of the Mg-Al casting alloys can observe: solid solution α with β ($Mg_{17}Al_{12}$) phase precipitations on grain boundaries and regions of lamellar mixture α+β. In addition, some regions of the so called divorced eutectic, precipitations of $MnAl_4$, and Al_8Mn_5 phases as well as Laves' Mg_2Si phases are to be found [7-9].

Magnesium alloys are subjected to heat treatment mostly for the purpose of improvement of their mechanical properties or as an intermediary operation, to prepare the alloy to other specific treatment processes. The type of heat treatment depends on the chemical composition of the alloy, its form (casting or after plastic working) and on the anticipated service parameters.

Precipitation hardening (marked T6 treatment) of magnesium alloys improves strength, with maximum ductility and shock. Solution treatment decreases strength due to dissolving of strengthening phases. Ageing after solution treatment gives maximum mechanical properties (tensile strength and yield point), with a decrease of ductility due to precipitation of metastable phases. Annealing (marked T5 treatment) lowers strength properties, casting stresses and increase ductility. Selection of the heat treatment parameters has an influence on microstructure and mechanical properties of magnesium alloy [10-12].

After solution treatment a solid solution of aluminium is present in magnesium (α) and possibly, some regions of undissolved continuous β ($Mg_{17}Al_{12}$) phase [13]. After ageing, two types of β ($Mg_{17}Al_{12}$) precipitations occur in Mg-9Al alloy: continuous and discontinuous. In most cases, the precipitations occur simultaneously. The continuous precipitation is a result of nucleation and growth of individual $Mg_{17}Al_{12}$ phase particles, which leads to changes in the matrix composition. Whereas discontinuous precipitations nucleate on the boundaries of the solid solution grains and when growing, they take the form resembling nodules [14]. Mg-Al alloys containing 5÷10 wt.-% of Al, are dominated by the continuous precipitations of $Mg_{17}Al_{12}$ phase. However, it has been found that the morphology of precipitations of the $Mg_{17}Al_{12}$ phase in Mg-Al alloys depends on the chemical composition (Al content) and temperature (Fig. 2).

It has been provided that:

1. Continuous precipitates of $Mg_{17}Al_{12}$ phase occur in the alloy when $T<T_{c1}$.
2. Continuous and discontinuous precipitates of the $Mg_{17}Al_{12}$ phase occur in the alloy when the temperature contains in range of $T_{c1}<T<T_{d1}$. When the temperature increases the area fraction of discontinuous precipitates increases.
3. Discontinuous precipitates of $Mg_{17}Al_{12}$ phase occur in the alloy when the temperature contains in range of $T_{d1}<T<T_{d2}$.
4. Similarly how in point 2, continuous and discontinuous precipitates of the $Mg_{17}Al_{12}$ phase occur in the alloy when the temperature contains in range of $T_{d2}<T<T_{c2}$. When the temperature increases the area fraction of discontinuous precipitates increases.
5. Only continuous precipitates of $Mg_{17}Al_{12}$ phase occur in the alloy when the temperature contains in range of $T_{c2}<T<T_s$.

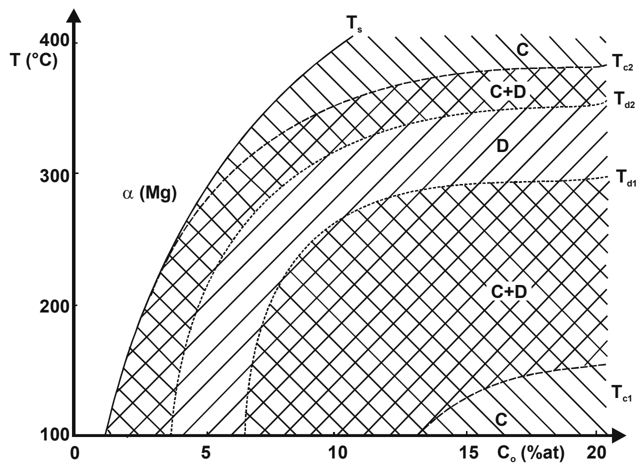


Fig. 2. Influence of Al content and temperature on the morphology of $Mg_{17}Al_{12}$ phase [13]

Critical temperature T_{c1} occurs mainly in alloys containing 18,8 at.-% of Al. Other temperatures occur in all commercial alloys. In Mg-Al alloys, continuous precipitation is prevailing at a high temperature (close to solvus line) and at a low temperature, whereas in the range of temperatures in-between, discontinuous precipitation prevails [14].

2. Description of the work methodology and material for research

2.1. Material for research

The material for the research was a GA8 magnesium alloy, cast into a sand mould. The chemical composition of the analysed alloy is shown in Table 1.

Table 1.
Chemical composition of the GA8 magnesium alloy in wt.-%.

Al	Zn	Mn	Si	Fe	Ni	Mg
8,7	0,7	0,23	0,04	0,006	0,001	balance

2.2. Research methodology

The study was conducted on GA8 magnesium alloys in as-cast condition and after heat treatment. The solution and ageing treatment parameters are presented on Figures 3 and 4 and in Table 2.

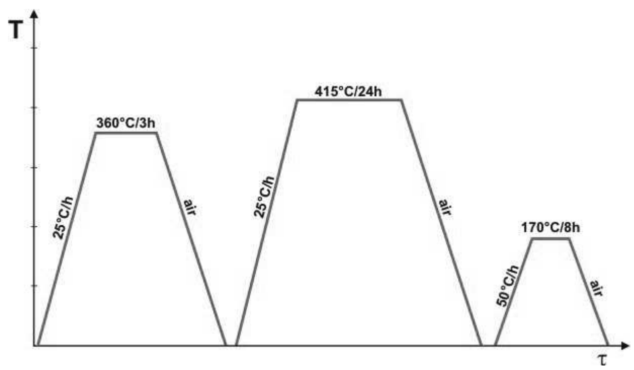


Fig. 3. Assessments of phases' surface fractions in the GA8 alloy structure after heat treatment

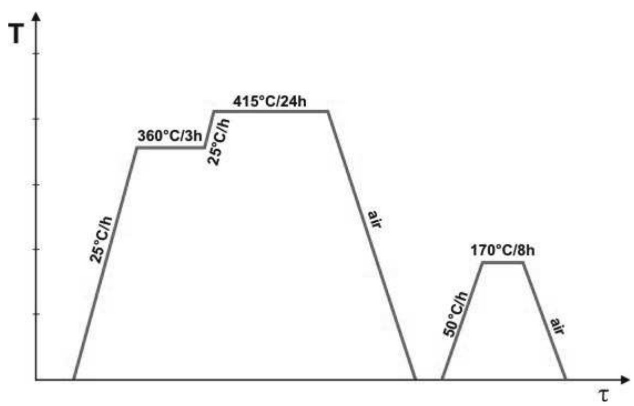


Fig. 4. Assessments of phases' surface fractions in the GA8 alloy structure after heat treatment

Table 2.
Parameters of the heat treatment.

Design.	Solution treatment			Ageing treatment		
	Temp. [°C]	Time [h]	Cooling	Temp. [°C]	Time [h]	Cooling
N	As-cast					
N1	360	3	air	-	-	-
N2	N1+415	24	air	-	-	-
N3	N1+N2			170	8	air
N4	1. 360 2. 415	3 24	- air	-	-	-
N5	N4			170	8	air

For microstructural observation, a Olympus GX+70 light microscope and a HITACHI S-3400N scanning electron microscope were used. Attempts to reveal the GA8 microstructure after heat treatment were made on the surface of the metallographic specimen. It has been found that:

- the best etching reagent for the alloy after solution treatment is reagent: 10 ml HF + 96 ml H_2O. Etching with this reagent allows for a clear identification of phases in the structure and for its qualitative description;
- in order to evaluate the grain size in the alloy after solution treatment, the etching reagent is: 20ml acetic acid + 80 ml H_2O + 5g $NaNO_2$;
- the best reagent for the alloy after ageing to be used for a qualitative and quantitative evaluation is: 5-20 ml acetic acid, 80-95 ml H_2O.

The quantitative evaluation of phases detected in the GA8 alloy after heat treatment was performed using a light microscope, OLYMPUS GX-71, equipped with an automatic Table for image stitching in XYZ axes and AnalySIS Pro® software as well as MetIlo® software [15].

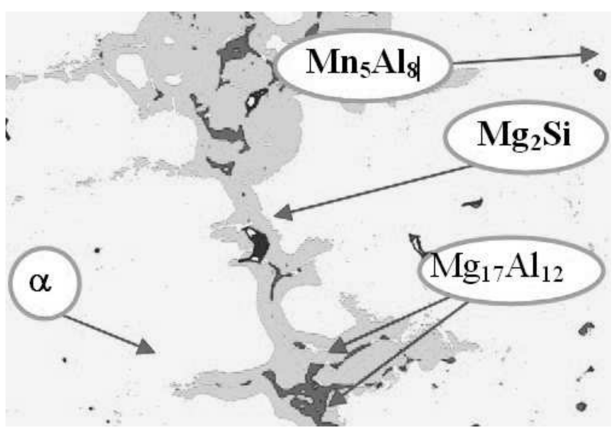
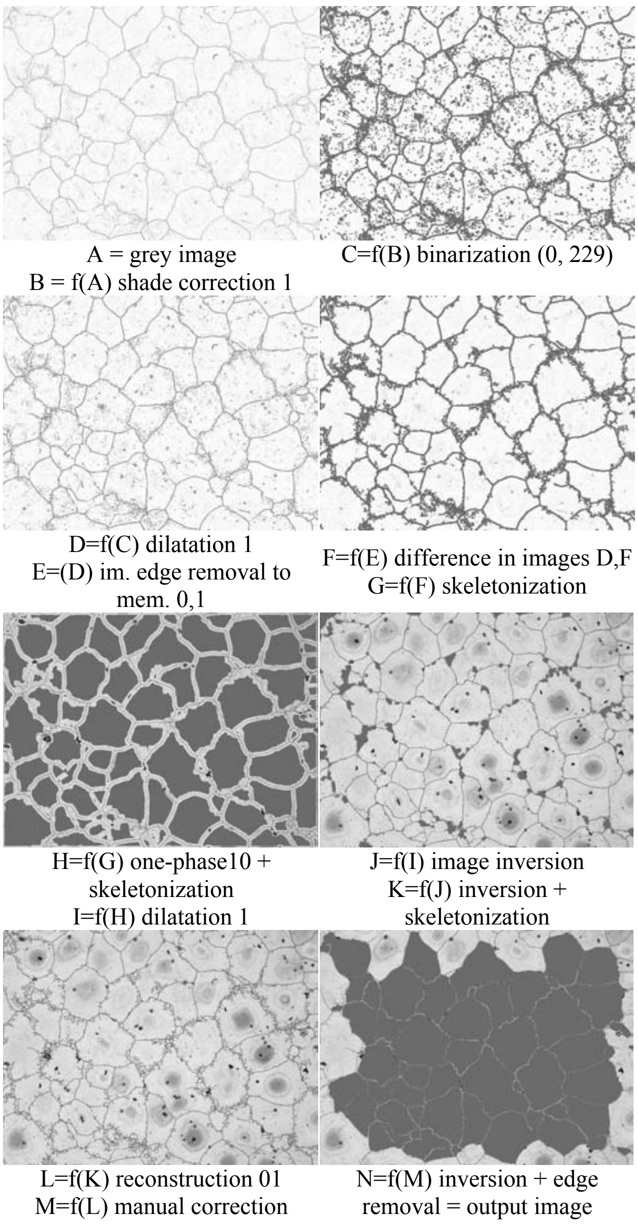


Fig. 5. Assessments of phases' surface fractions in the GA8 alloy structure after heat treatment

For the evaluation of phases' area fraction, the AnalySIS Pro® program was used. It was assumed that, based on the metallographic investigations, the surface fractions of the following phases would be analysed: continuous $Mg_{17}Al_{12}$ phase, discontinuous $Mg_{17}Al_{12}$ phase and regions enriched with Al, Mg_2Si phase and the area occupied by solid solution α. The selective detection of phases is shown in Fig. 5.

For grain size measurement, an automated image analysis facility based on the MetIlo® software was used. A set of grey image transformations until obtaining a binary image are shown in Fig. 6.



A = grey image
B = f(A) shade correction 1
C=f(B) binarization (0, 229)
D=f(C) dilatation 1
E=(D) im. edge removal to mem. 0,1
F=f(E) difference in images D,F
G=f(F) skeletonization
H=f(G) one-phase10 + skeletonization
I=f(H) dilatation 1
J=f(I) image inversion
K=f(J) inversion + skeletonization
L=f(K) reconstruction 01
M=f(L) manual correction
N=f(M) inversion + edge removal = output image

Fig. 6. Set of grey image transformations to a binary image

3. Description of achieved results of own researches

3.1. Microstructure of the GA8 magnesium alloy in as-cast condition

The microstructure of GA8 magnesium alloy has a solid solution structure α with α + discontinuous β areas and continuous β ($Mg_{17}Al_{12}$) phase at grain boundaries. Moreover, the occurrence of Laves' phase in the form of Mg_2Si and other precipitates, probably of Mn_5Al_8 phase, has been provided (Fig.7) [16]. The mapping of Mg, Al, Mn can be seen in Figure 8.

The average area fraction of continuous β phase was A_A=6.65% and discontinuous (α+β areas) was A_A=19.99% (Table 3). The area fraction of Mg_2Si phase was equal A_A=0,15%. The mean plane section area of the solid solution grain size was $\bar{A}$ = 5442 μm^2.

a)

b)

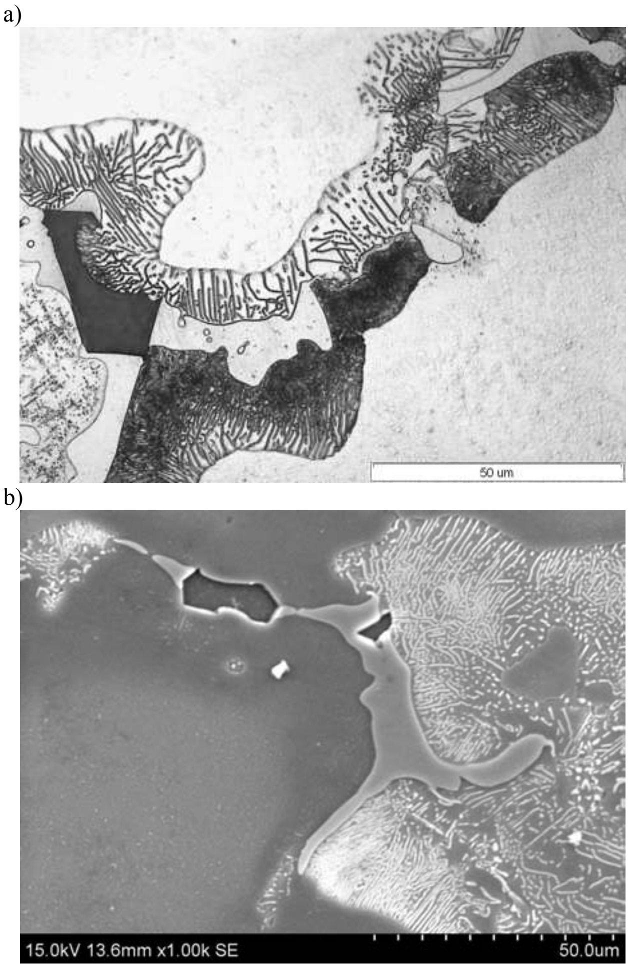


Fig. 7. Microstructure of the as-cast GA8 alloy (sample N), a) LM image, b) SEM image

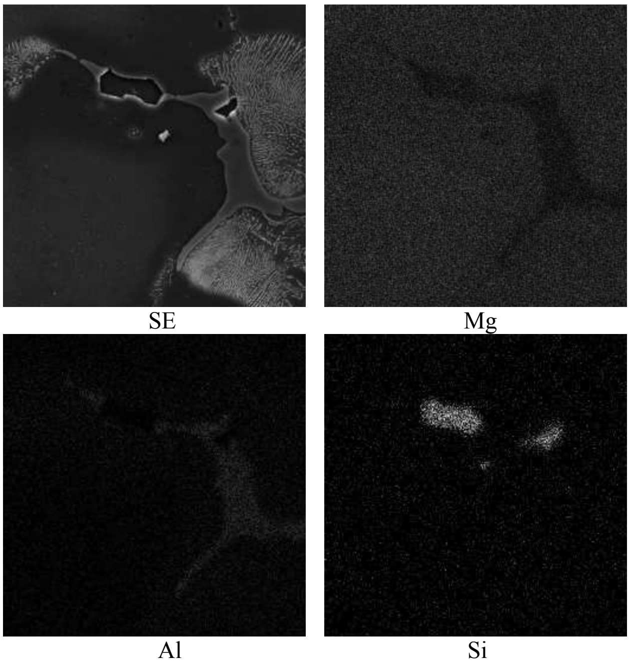


Fig. 8. The SE image and the distribution of Mg, Al, Mn in microareas of GA8 magnesium alloy

Table 3.
Assessment of phases' area fractions in the GA8 alloy microstructure in as cast condition (specimen N).

Phase	Area fraction A_A [%]			Variability index [%]
	Min.	Max.	Mean	
$Mg_{17}Al_{12}$ (cont)	5,55	9,38	6,65	16
$Mg_{17}Al_{12}$ (discont)	16,04	23,8	19,99	14
Solution α	69,86	76,86	73,15	4
Mg_2Si	0,1	0,2	0,15	21

3.2. Microstructure of the GA8 magnesium alloy after solution treatment

After solution treatment a reduction of the number of β phase precipitations was observed. Solution treatment at 360°C/3h with air cooling led to reduction of discontinuous β phase area fraction to A_A=5.55% and continuous β phase area fraction to A_A=3.44% (Table 4). The area fraction of Mg_2Si phase was equal A_A=1.34%. The mean plane section area of solid solution α grain grew to A=6798 μm^2 (Fig.9).

Solution treatment at a temperature of 415°C, after treatment at 360°C caused a considerable (4-times) decrease of the β phase quantity compared to the state after treatment at 360°C [16]. The area fraction of continuous β phase decrease to A_A=1.2%. The precipitates of discontinuous β phase weren't observed (Table 4). The area fraction of Mg_2Si phase was equal A_A=0.35%. The mean plane section area of the solid solution α grain increased to $\bar{A}$=7554 μm^2 and was higher compared to the initial state (Fig.10).

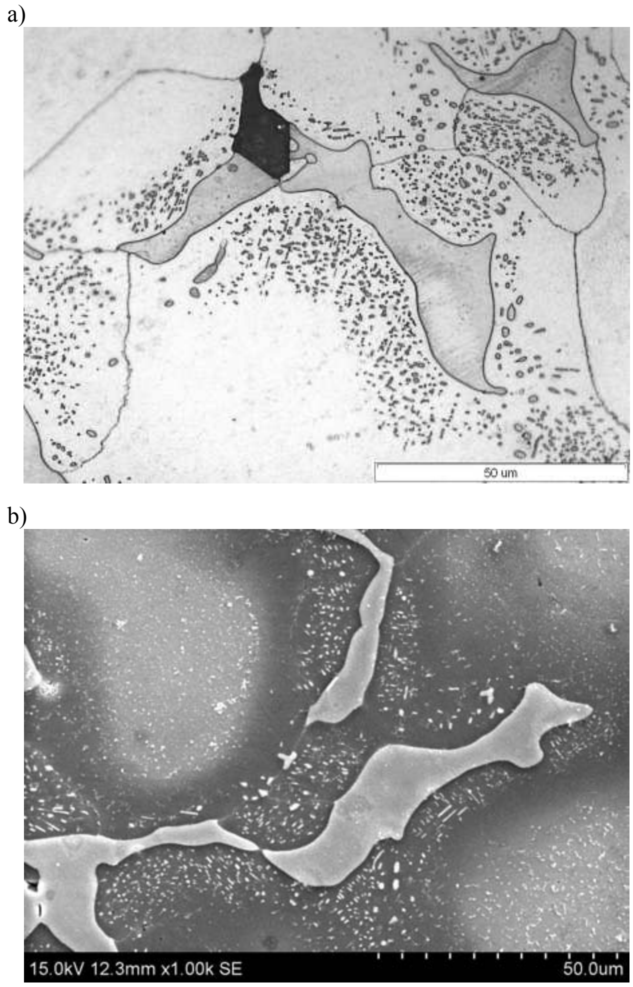


Fig. 9. Microstructure of the GA8 alloy after solution treatment 360°C/3h/air (sample N1), a) LM image, b) SEM image

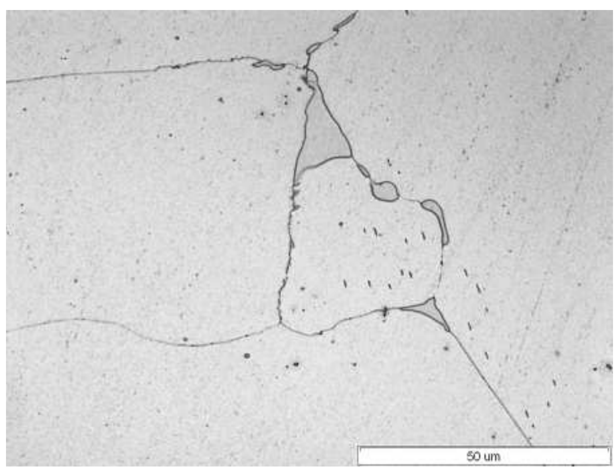


Fig. 10. Microstructure of the GA8 alloy after solution treatment 360°C/3h/air+415/24/air (sample N2)

Table 4.
Assessment of phases' area fractions in the GA8 alloy microstructure after solution treatment

	Phase	Area fraction A_A [%]			Variability index [%]
		Min.	Max.	Mean	
N1	$Mg_{17}Al_{12}$ (cont)	2,3	4,82	3,44	27
N1	$Mg_{17}Al_{12}$ (discont)	3,27	7,46	5,55	23
N1	Solution α	85,79	90,75	88,3	19
N1	Mg_2Si	0,92	1,74	1,34	23
N2	$Mg_{17}Al_{12}$ (cont)	0,79	1,89	1,2	29
N2	$Mg_{17}Al_{12}$ (discont)	0	0	0	0
N2	Solution α	96,6	98,19	97,62	0,5
N2	Mg_2Si	0,29	0,39	0,35	10
N4	$Mg_{17}Al_{12}$ (cont)	0,19	0,71	0,46	46
N4	$Mg_{17}Al_{12}$ (discont)	0,5	1,11	0,82	23
N4	Solution α	95,45	97,57	96,08	0,9
N4	Mg_2Si	0,05	0,16	0,1	33

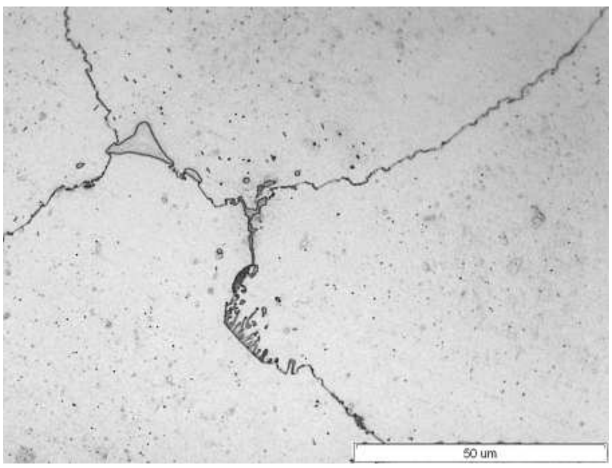


Fig. 11. Microstructure of the GA8 alloy after solution treatment 360°C/3h+415/24air (sample N4)

After solution treatment at 360°C/3h/without cooling and 415/24/air (Fig.4) also a reduction of the number of β phase precipitations was observed [16]. This treatment led to reduction of discontinuous β phase area fraction to A_A=0,82% and continuous β phase area fraction to A_A=0,46%. The area fraction of Mg_2Si phase was equal A_A=0.1% (Table 4). The mean plane section area of solid solution α grain was $\bar{A}$=7544 μm^2 (Fig.11).

3.3. Microstructure of the GA8 magnesium alloy after ageing treatment

Application of ageing treatment caused precipitation of discontinuous β phase (Fig. 12, 13) [16].

The ageing treatment 170°C/8h/air applied after solution treatment 360°C/3h/air+415/24/air (Fig.3) caused increase of discontinuous β phase area fraction to A_A=11,03%, but did not influence to the number of continuous β phase precipitates (A_A=1,07%) compared to the state after solution treatment (Fig.12). The area fraction of Mg_2Si phase was equal A_A=0.37% (Table 4).

a)

b)

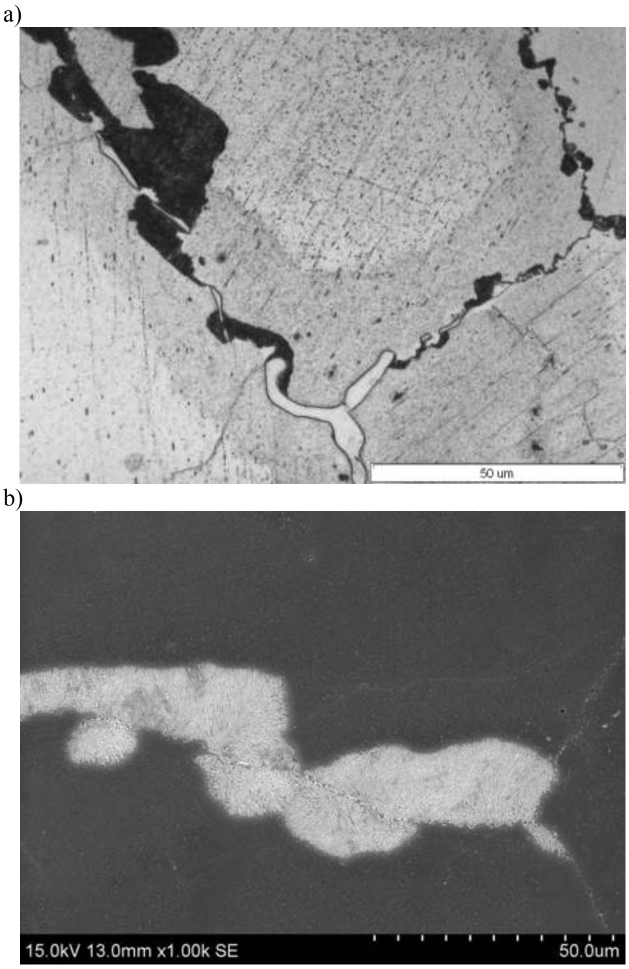


Fig. 12. Microstructure of the GA8 alloy after solutioning 360°C/3h/air+415/24/air and ageing 170°C/8h/air (sample N3), a) LM image, b) SEM image

The ageing treatment applied after solution treatment 360°C/3h/without cooling + 415/24/cooling in air (Fig.4) also caused increase of discontinuous β phase area fraction (A_A=2,72%), but this increase was very small. The area fraction of continuous β phase was slightly higher (A_A=2.55%) compared to the state after solution treatment (Fig.13). The area fraction of Mg_2Si phase was equal A_A=0.15% (Table 5).

After ageing treatment the mean area of the solid solution α grain did not change.

a)

b)

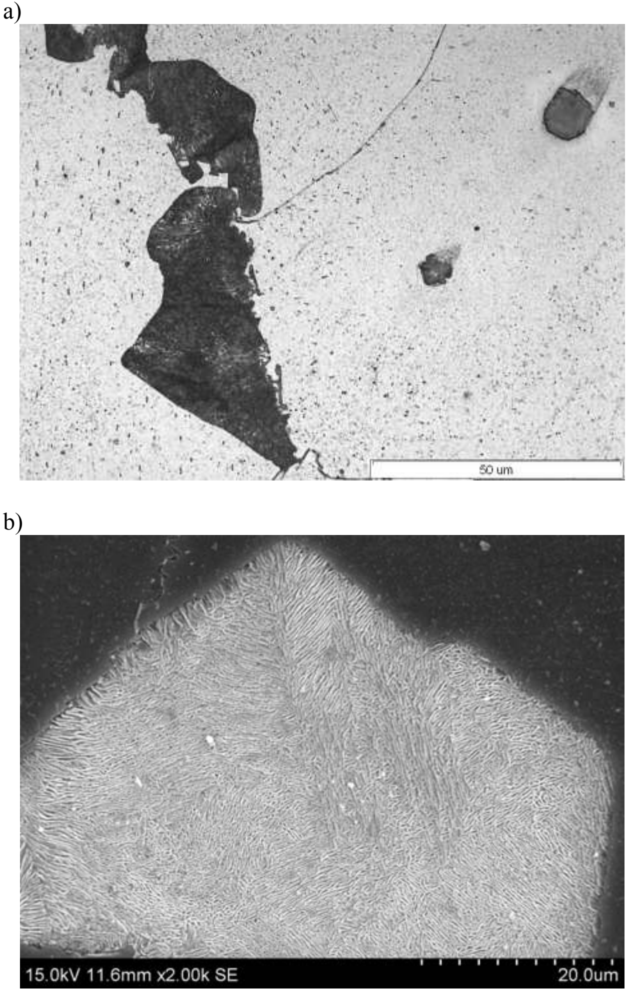


Fig. 13. Microstructure of the GA8 alloy after solution treatment 360°C/3h+415/24/air and ageing 170°C/8h/air (sample N5), a) LM image, b) SEM image

Table 5.
Assessment of phases' area fractions in the GA8 alloy microstructure after ageing treatment

	Phase	Area fraction A_A [%]			Variability index [%]
		Min.	Max.	Mean	
N3	$Mg_{17}Al_{12}$ (cont)	0,49	2,32	1,07	43
	$Mg_{17}Al_{12}$ (discont)	4,28	16,27	11,03	27
	Solution α	74,56	90,02	80,75	5
	Mg_2Si	0,25	0,72	0,37	32
N5	$Mg_{17}Al_{12}$ (cont)	0,5	5,67	2,55	76
	$Mg_{17}Al_{12}$ (discont)	1,49	5,38	2,72	44
	Solution α	86,53	97,38	93,39	3,8
	Mg_2Si	0,07	0,24	0,15	39

4. Summary

The aim of the investigations was qualification of precipitation hardening parameters on the GA8 magnesium alloy microstructure. A cast of the GA8 magnesium alloy shows the presence of continuous and discontinuous precipitates of β ($Mg_{17}Al_{12}$) phase at the solid-solution grain boundaries, Moreover, the occurrence of Mg_2Si and Mn_5Al_8 phases has been provided.

After solution treatment at a temperature of 360°C/3h/air the area fraction of discontinuous and continuous β ($Mg_{17}Al_{12}$) phase precipitates significantly decreased from A_A=19.99% (as cast state – sample N) to A_A=5.55% and from A_A=6,65% to A_A=3.44%, respectively (Fig.14). After fully solution treatment (samples N2 and N4) at 415°C/24h/air almost fully dissolution of both types of β ($Mg_{17}Al_{12}$) phase has been observed. The area fraction of discontinuous β phase decreased to A_A=0% (sample N2) and to A_A=0.82% (sample N4). The area fraction of continuous β phase decreased to A_A=1,2% (sample N2) and to A_A=0.46% (sample N4).

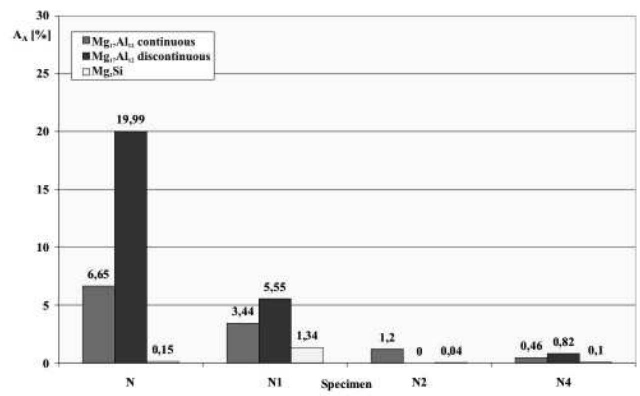


Fig. 14. Influence of the solution treatment on the β phase quantity

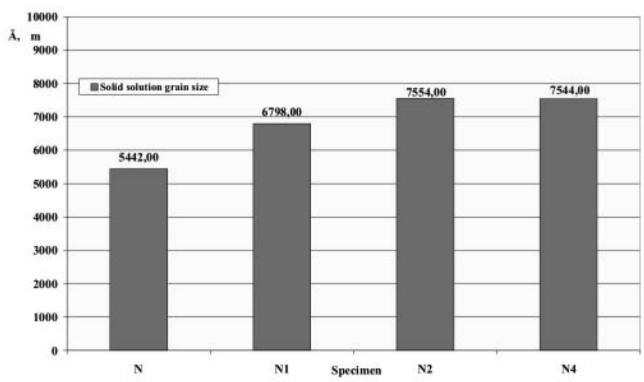


Fig. 15. Influence of the solution treatment on the solid solution grain size

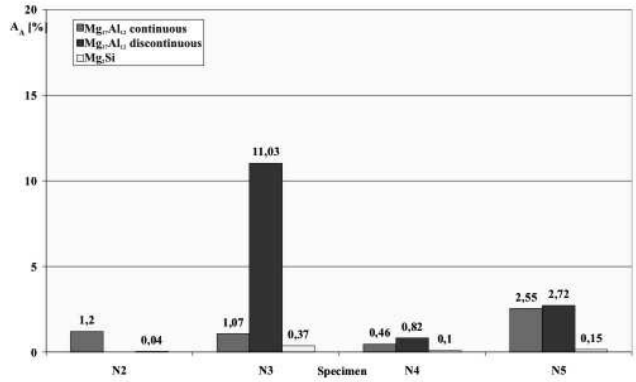


Fig. 16. Influence of the ageing treatment on the β phase quantity

Solution treatment parameters did not significant influence on the mean plane section area of solid solution α grain (Fig.15). In the initial state the mean plane section area of solid solution α grain was equal $\bar{A} = 5442\ \mu m^2$. After solution treatments designated N2 and N4 the mean plane section area slightly increase to $\bar{A} = 7554\ \mu m^2$ and $\bar{A} = 7544\ \mu m^2$, respectively.

After aged 8h at 170°C (same N3) GA8 alloy is characterized by discontinuous β phase along the solid solution grain boundaries. Area fraction of the discontinuous β phase increased from A_A=0% to A_A=11.03%. The area fraction of the continuous β phase was constant (Fig.16). Similarly how sample N3 kept sample N5. The area fraction of the discontinuous and continuous β phase increased to A_A=2.72% and A_A=2.55%, respectively (Fig.16).

5. Conclusions

Based on the experimental results obtained, the following conclusions can be drawn:

1. The GA8 alloy structure in as cast condition is characterized by a solid solution structure α with α + discontinuous β areas and continuous β ($Mg_{17}Al_{12}$) phase at grain boundaries. The mean plane section area of solid solution α grain equals $\bar{A}$=5442 μm^2. The average area fraction of continuous β phase is A_A=6.65% and discontinuous (α+β areas) is A_A=19.99%
2. After solution treatment at 360°C/3h/with or without air cooling + 415°C/24/air a reduction of the number of continuous and discontinuous β ($Mg_{17}Al_{12}$) phase precipitates is observed. The mean plane section area of solid solution α grain did not significantly change.
3. After ageing the GA8 magnesium alloy is characterized by discontinuous β phase along the solid solution grain boundaries.
4. Ageing treatment at 170°C/8h after solution treatment 360°C/3h/without air cooling + 415°C/24/air cause more significant decrease of discontinuous β phase area fraction to A_A=11.03% comparing to solution treatment with air cooling after heating at 360°C A_A=2.72% .

Acknowledgements

This work was supported by the Polish Ministry of Education and Science under the research project No. 6 ZR7 2005 C/06609.

References

[1] H. Friedrich, S. Schumann, Research for a "new age of magnesium" in the automotive industry, Journal of Materials Processing Technology 117 (2001) 276-281.
[2] L. Čížek, M. Greger, L. Pawlica, L.A. Dobrzański, T. Tański, Study of selected properties of magnesium alloy AZ91 after heat treatment and forming, Journal of Materials Processing Technology 157-158 (2004) 466-471.
[3] E. Aghion, B. Bronfin, D. Eliezer, The role of magnesium industry in protecting the environment, Journal of Materials Processing Technology 117 (2001) 381-385.
[4] A.A. Luo, Magnesium current and potential automotive applications, Journal of Materials Processing Technology 54 (2002) 42-47.
[5] A. Dahle, Y. Lee, M. Nave, P. Schaffer, D.St. John, Development of the as-cast microstructure in magnesium-aluminium alloys, Journal of Light Metals 1 (2001) 61-72.
[6] L.A. Dobrzański, T. Tański, L. Čížek, Influence of Al addition on structure of magnesium casting alloys, Journal of Achievements in Materials and Manufacturing Engineering 17 (2006) 221-224.
[7] J. Adamiec, A. Kiełbus, J. Cwajna, Microstructure of the GA8 casting magnesium alloy, Archives of Foundry 18 (2006) 203-208.
[8] A. Kiełbus, M. Sozańska, L. Čížek, Microstructural behavior of AZ91D magnesium alloy during heat treatment, Materials Engineering 3 (2004) 364-367.
[9] A. Kiełbus, T. Rzychoń, R. Cibis, Microstructure of AM50 die casting magnesium alloy, Journal of Achievements in Materials and Manufacturing Engineering 18 (2006) 135-138.
[10] C.H. Caceres, C.J. Davidson, J.R. Griffiths, C.L. Newton, Effects of solidification rate and ageing on the microstructure and mechanical properties of AZ91 alloy, Materials Science and Engineering A325 (2002) 344-355.
[11] P.F. Stratton, E.K. Chamg, Protective atmospheres for the heat treatment of magnesium alloys, TMS Annual Meeting, Symposium: Magnesium Technology 2000.
[12] E. Cerri, M. Cabobbo, E. Evangelista, Microstructural evolution during high-temperature exposure in a thixocast magnesium alloy, Materials Science and Engineering A333 (2002) 208-217.
[13] M. Zhang, P.M. Kelly, Crystallography of $Mg_{17}Al_{12}$ precipitates in AZ91D alloy, Scripta Materialia 48 (2003) 647-652.
[14] D. Duly, J.P. Simon, Y. Brechet, On the competition between continuous and discontinuous precipitations in binary Mg-Al alloys, Acta Metallurgica et Materialia 43 (1995) 101-106.
[15] A. Kiełbus, J. Adamiec, J. Cwajna, J. Paśko, The influence of heat treatment on the microstructure of GA8 magnesium alloy, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 131-134.