INFLUENCE OF HEAT TREATMENT ON PROPERTIES OF EN AW 6082 ALUMINIUM ALLOY

Petra Lacková[1)], Marián Buršák[1)], Ondrej Milkovič[1)], Marek Vojtko[1)], Lukáš Dragošek[2)]*
[1)] Technical University of Košice, Faculty of Metallurgy, Department of Materials Science, Košice, Slovakia
[2)] Technical University of Košice, Faculty of Metallurgy, Department of Metal Forming, Košice, Slovakia

Received: 20.03.2015
Accepted: 24.03.2015

*Corresponding author: *e-mail: petra.lackova@tuke.sk, Tel.: +421 55 602 2782, Department of Materials Science, Faculty of Metallurgy, Technical University of Košice, Letná 9, 042 00 Košice, Slovakia*

Abstract
The main aim of this work is to point out on possibility of properties improving of the aluminium alloy EN AW 6082 (AlSi1MgMn) with an appropriate combination of pre-ECAP solution annealing, the application of the severe plastic deformation by ECAP technology (equal channel angular pressing) and post-ECAP artificial aging. The effect of the severe plastic deformation and artificial aging on the alloy structure was evaluated by metallographic analysis, and alloy mechanical properties by uniaxial tensile test at room temperature, the Vickers hardness and by tribology test of resistance to abrasive wear. As a result of strain hardening by severe plastic deformation it reaches the improvement in hardness (by 56%), strength characteristics (yield strength by 92%, tensile strength by 29%) and abrasion wear resistance is 28 %.

Keywords: severe plastic deformation, tension test, aluminium alloys, wear

1 Introduction

The aluminium alloys belonging to 6XXX groups, which are widely used in structural applications, the construction industry, the automotive industry and architectural section as extrusions products [1]. AlSi1MgMn alloy is characterized by good mechanical properties, resistance to tribology (abrasion wear) and corrosion degradation, low density. Due to good tribological properties of alloy can be used in excellent application. These properties can be increased by strengthening mechanisms: alloying additives respectively heat treatment and the severe plastic deformation [2-3].

The AlSi1MgMn alloy is alloyed from the main elements namely magnesium and silicon. At higher magnesium content tends to increase strength properties of hardened alloy formation of Mg_2Si phase. Silicon improves mechanical properties by changing the shape of the grain. Except of the main alloying elements, there are added the alloy chromium and manganese which form dispersion particles. These are larger than the other precipitates that can act as nucleation sites for strengthening precipitations, and have good thermal stability, which influences the recovery and recrystallization [4-6]

Another way of improving the properties of the alloy is heat treatment (consisting of solution treatment, quenching in water, and a natural or artificial ageing treatment). From the

DOI 10.12776/ams.v21i1.553 p-ISSN 1335-1532
e-ISSN 1338-1156

supersaturated solid solution (SSSS) during aging alloy going to be stable. According to the authors [7-10] the precipitation sequence proceeds as follows: SSSS → GP zone→pre-β´´($(Al+Mg)_5Si_6$)→ β´´ (Mg_5Si_6, Al_3MgSi_6)→ β´ (Mg_9Si_5), B´, U1 ($MgAl_2Si_2$, $MgAl_4Si_5$), U2($Mg_2Al_4Si_5$, MgAlSi)→ β (Mg_2Si). The coherent metastable phase B ', U1 and U2 coexists with β'-phase transition [11-12]. The formation of the equilibrium β phase (Mg_2Si) there is significant strengthening of the alloy. With the increasing ratio of Mg:Si, the strength of the alloy is higher [13]. Addition of copper in the alloy formed transition Q´ phase ($Al_4CuMg_6Si_6$) and stable Q phase ($Al_4Cu_2Mg_8Si_7$).Due to the low diffusion of copper into α-Al and subsequent coarsening Q'phase, alloys are thermally stable [14-16]. On the other hand, the alloys with copper have low corrosion resistance [17-18]. The significant improvement in properties of the alloy can be achieved by a suitable combination of mentioned heat treatment followed by application the severe plastic deformation. Influence of the severe plastic deformation is to achieve ultra-fine grained structure optionally nanostructure [19-23]. ECAP technique (Equal channel angular pressing) is the most used technique from the severe plastic deformation methods. The principle of the extruded material through a die consists of two perpendicular channels. The material is in the transition of shear without changing of it is cross-sectional [24-26].

The goals of this present work are to determine the optimal temperature pre-ECAP solution annealing and post-ECAP artificial aging evaluation of changes hardness and examine the change characteristics of aluminium alloy AlSi1MgMn from the initial state and the state after heat treatment (pre-ECAP solution annealing + water + cooling extrusion through the ECAP die + post-ECAP artificial aging).

2 Experimental material and methodology of experiments

As experimental material has been used commercially produced the aluminium alloy AlSi1MgMn with the chemical composition shown in **Table 1**. The samples were delivered in a form of bars with heat treatment T3 (solution annealing and natural aging).

Table 1 The chemical composition of AlSi1MgMn [wt. %]

Material	Al	Cr	Cu	Fe	Mg	Mn	Si	Zn
AlSi1MgMn	rest.	0.25	0.10	0.50	0.60	0.40	0.70	0.20

For the determination of optimum conditions for pre-ECAP solution annealing, the alloy was carried out experiments at five different temperatures of 530, 540, 550, 560 and 570 °C with holding time 1.5 h during which the measured hardness **Fig. 1**.

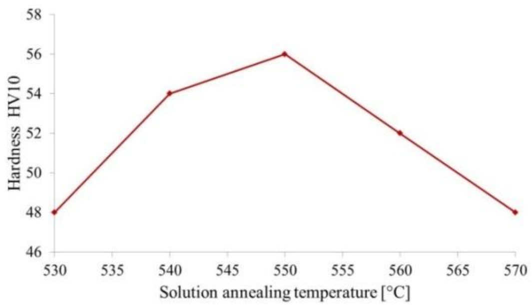

Fig. 1 Influence of solution annealing temperature on the hardness HV10

DOI 10.12776/ams.v21i1.553
p-ISSN 1335-1532
e-ISSN 1338-1156

After determining suitable parameters the aluminium alloy was subjected to the severe plastic deformation by technology ECAP under the following conditions: route B_c extrusion speeds with one pass 75 $mm.min^{-1}$, second pass 30 $mm.min^{-1}$ and third pass 20 $mm.min^{-1}$.The macrostructure of the broken specimen after four passes is documented in **Fig. 2**.

Fig. 2 Macrostructure od the specimen after four passes

After the severe plastic deformation it follows the post-ECAP artificial ageing. As in the case of pre-ECAP solution annealing there were performed experiments with five different temperatures artificial aging 80, 90, 100, 110 and 120 °C and holding time 30hduring which the hardness measures **Fig. 3**. Suitable temperature for pre-ECAP and post-ECAP was based on the peak value of hardness HV10.

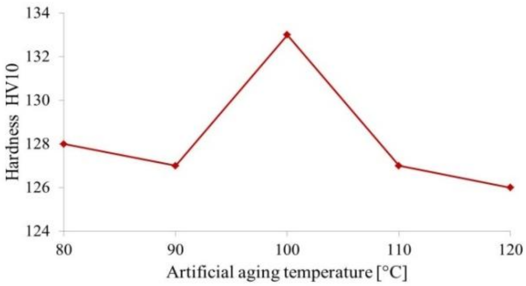

Fig. 3 Influence of artificial aging temperature on the hardness HV10

The experiments for pre-ECAP and post-ECAP treatments were performed on the samples with optimal conditions. The samples for metallographic analysis were prepared by standard procedures: grinding, polishing on the diamond paste and emulsion OP-S Suspension followed by etching with a solution of Kroll (92 ml distilled water, 6 ml HNO_3, 2 ml HF). The microstructures were observed and documented using the light microscope OLYMPUS Vanox-T. The thin foils were prepared by double jet electro polishing in TenuPol - 5. The microstructures were observed using transmission electron microscopy Jeol JEM 200 FX in the bright field images(operated at 200 kV). Strength and plastic characteristics were measured by uniaxial tensile test at room temperature on a Zwick 1387 machine at a speed of 0.5 mm / min. The Vickers hardness was measured at a load of 95 N. The abrasive wear was carried out on the SVUM-AB-1 machine with a load of 5 N with the track 40 m using sandpaper with aluminium particles and roughness120. The prepared samples were weighed before and after the experiment to within ± 0.0001 g. The fracture surfaces and the surfaces of the abrasive wear were studied using scanning electron microscope JEOL JSM 7000F.The particles identification was carried out using the EDX analysis with the analyser INCA-sight.

3 Results and discussion

The surfaces of samples in the initial state and after post-ECAP artificial aging are documented in **Fig. 4** and **Fig. 5**. The microstructure of AlSi1MgMn alloy is characterized intermetallic phasesMg_2Si, AlFe, AlFeSi, $Al_{15}(FeMn)_3Si_2$, $Al_5Cu_2Mg_8Si_6$ [27].

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e-ISSN 1338-1156

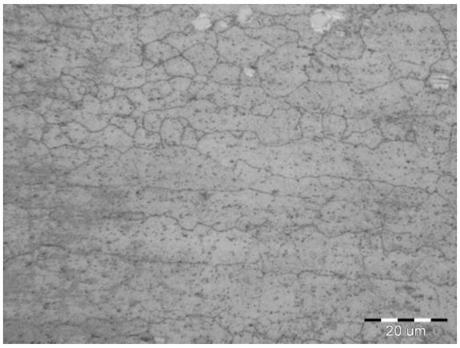

Fig. 4 Microstructure of AlSi1MgMn in initial state

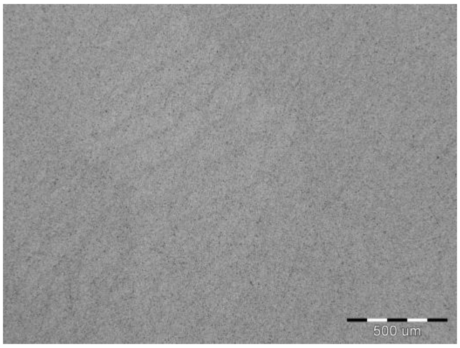

Fig. 5 Microstructure of AlSi1MgMn in post-ECAP artificial aging

The EDX analysis in both treatments showed presence of phases based on MgSi, AlFeMnSi, AlSiMg (**Fig. 6** and **Fig. 7**). The microstructure after post-ECAPartificial aging is characterized by deformation bands that characterize the uneven deformation after the sample cross-section.

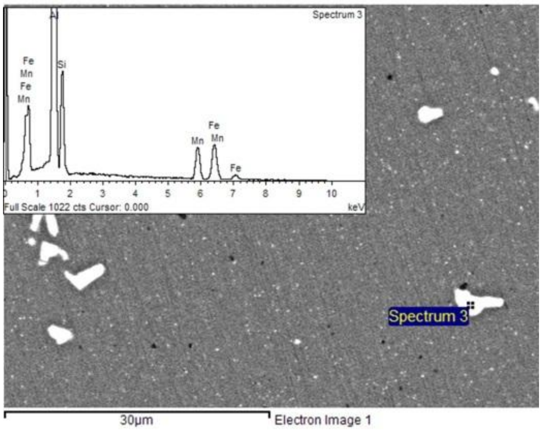

Fig. 6 EDX analyses of AlSi1MgMn in initial state

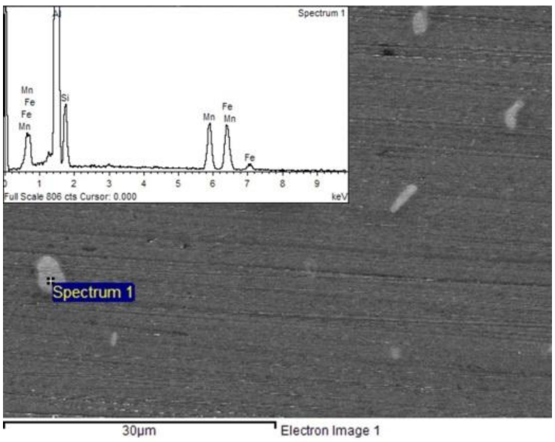

Fig. 7 EDX analyses of AlSi1MgMn in post-ECAP artificial aging

DOI 10.12776/ams.v21i1.553 p-ISSN 1335-1532
e-ISSN 1338-1156

The microstructures observed by TEM are documented in the **Fig. 8** and **Fig. 9**. The average size of grains was 4 μm in initial state and under 0.3 μm after post-ECAP state. After post-ECAP artificial aging the microstructure was not recrystallized. The recovery and changes of dislocation density were not visible in the microstructures after post-ECAP artificial aging.

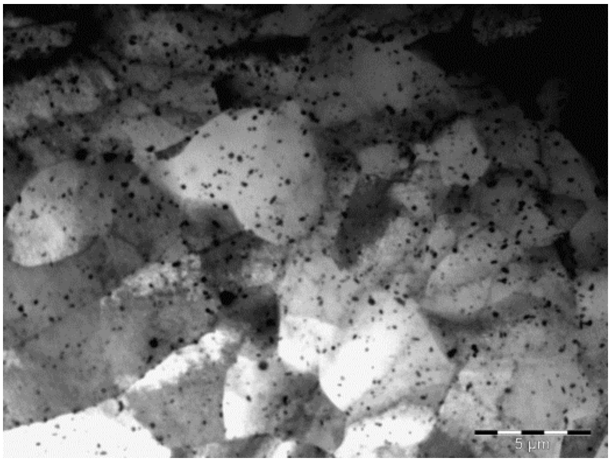

Fig. 8 Microstructure observed by TEM in initial state

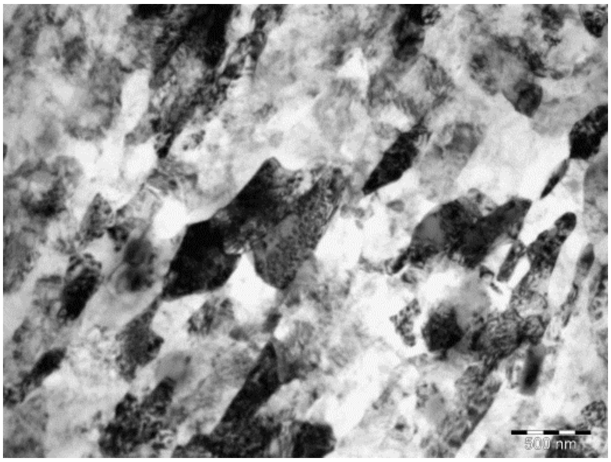

Fig. 9 Microstructure observed by TEM in post-ECAP artificial aging

The courses of tensile stress-strain curves at uniaxial tensile test are documented in Fig. 10.The values of strength and hardness characteristics are shown in the Table 2. After post-ECAP artificial aging increased yield strength by 96%, tensile strength by 30% and hardness by 56%.The ratio YS/ UTS compared with initial state increased the value from 0.62 to 0.94.On the other hand, the plastic characteristics have decreased elongation by 25% and contraction by 23%.The modulus of elasticity after post-ECAP artificial aging not changed. It is caused due to severe plastic deformation during which there was an accumulation of deformation in the alloy causing the strain hardening and engendered exhaustion.

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e-ISSN 1338-1156

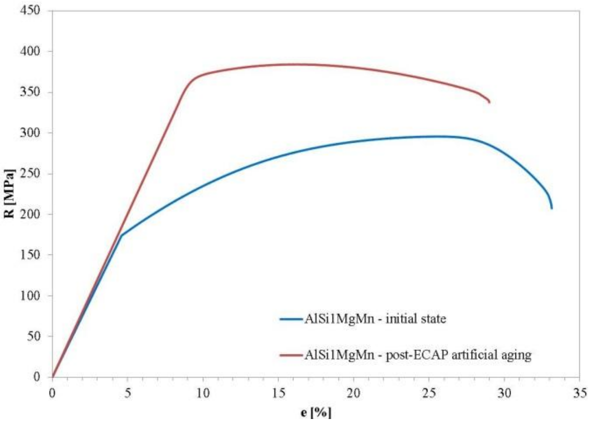

Fig. 10 Tensile stress-strain curves of initial state and post-ECAP artificial aging

Table 2 Mechanical properties of AlSi1MgMn

state	YS[MPa]	UTS [MPa]	e [%]	E [GPa]
initial	185	298	27.5	70.0
post-ECAP artificial aging	364	387	20.6	70.2

The fracture surfaces after static tension tests are documented in **Fig. 11** and **Fig. 12**. In both cases, we are talking about transgranular ductile fracture with pit morphology. The identified particles found in the dimple are based on: AlFeMnSi, AlSiMgMn and AlSiMgMnFe.

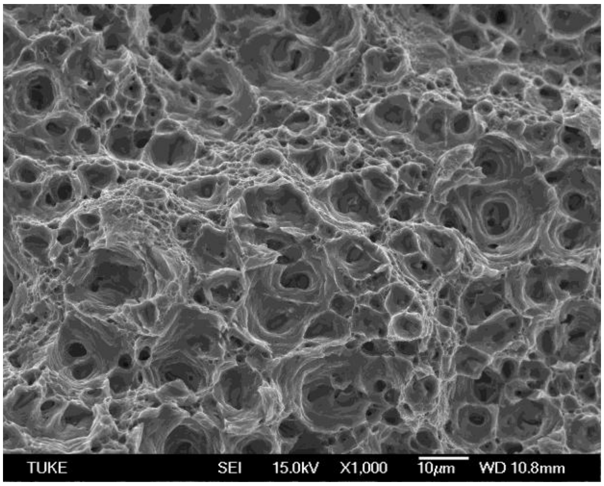

Fig. 11 Fracture surface of initial state

The average weight loss results after abrasive wear are shown in **Table 3**. From the resulting values can be seen that the wear resistance is low in the initial state. The severe plastic deformation increased strength characteristics, hardness and also abrasive wear resistance. The relative abrasive wear resistance represents the histogram depicted in a **Fig. 13**.

DOI 10.12776/ams.v21i1.553 p-ISSN 1335-1532
e-ISSN 1338-1156

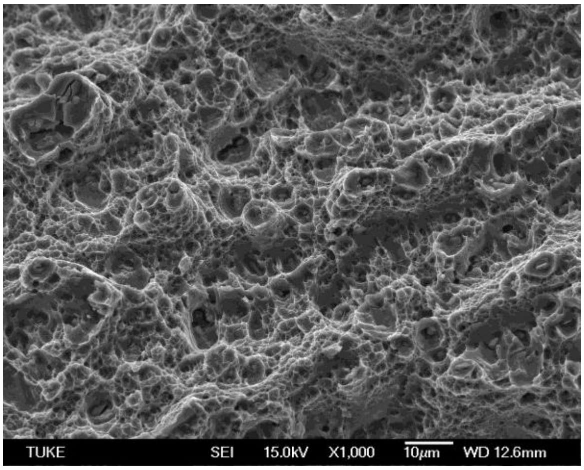

Fig. 12 Fracture surface of post-ECAP artificial aging

Table 3 Weight losses of samples after abrasion wear

	State	Average weight loss [g]
AlSi1MgMn	initial state	0.1088
	post-ECAP artificial aging	0.0774

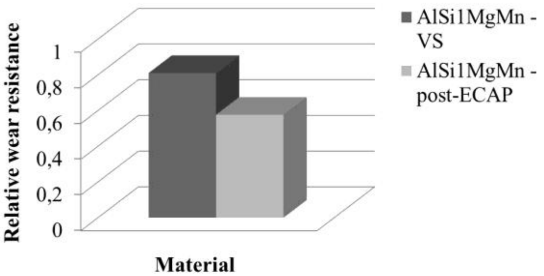

Fig. 13 Relative abrasive wear resistance of lSi1MgMn

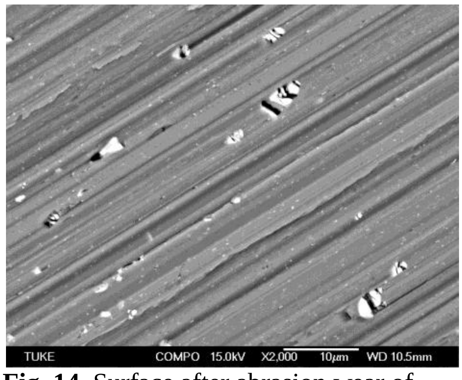

Fig. 14 Surface after abrasion wear of initial state

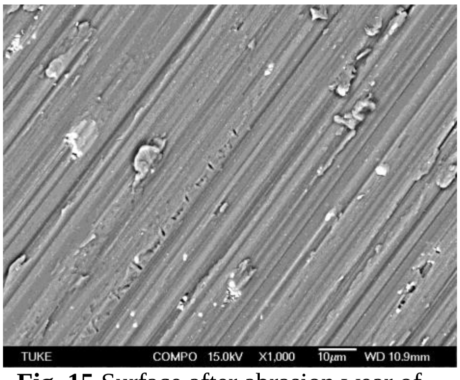

Fig. 15 Surface after abrasion wear of post-ECAP artificial aging

DOI 10.12776/ams.v21i1.553
p-ISSN 1335-1532
e-ISSN 1338-1156

The surfaces of the samples after abrasive wear in mode backscattered electrons are shown in **Fig. 14** and **Fig. 15**. In both cases, the observed degradation of the surface grooves. This is caused due to chipping of the particles of the abrasive paper which are pressed into the surface of the material. The detailed mechanical damage, cracking and breaking of the particles is documented in **Fig. 16** and **Fig. 17**.

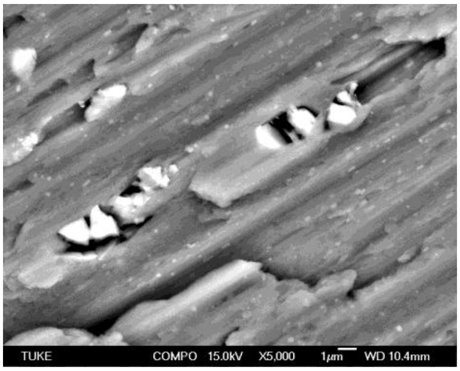

Fig. 16 Surface detail after abrasion wear of initial state

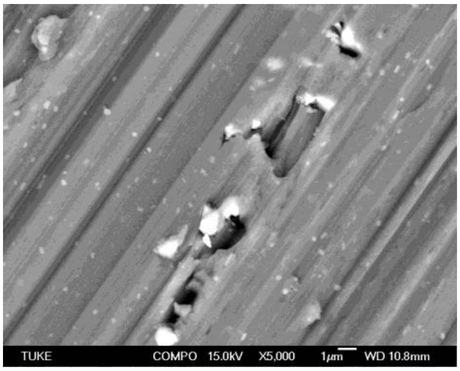

Fig. 17 Surface detail after abrasion wearof post-ECAP artificial aging

4 Conclusions

Based on the results of the experimental part, it is possible to note the following:

- optimum heat treatment for the alloy was achieved under the conditions: pre-ECAP solution annealing 550 °C / 1.5 h + 3x ECAP + post-ECAP artificial aging by 100 °C / 30 h,
- microstructures in both states are composed of particles based on: MgSi, AlFeMnSi, AlSiMg, however after post-ECAP artificial aging the microstructure is characterized by uneven deformation,
- size of grains after post-ECAP artificial aging decreased from 4μm to 0.3 μm,
- hardness by Vickers increased after post-ECAP artificial aging by 56 %,
- mechanical properties after post-ECAP artificial aging increased: yield strength by 96 %, tensile strength by 30 %, on the other hand plastic properties decreased: elongation by 25%, contraction by 23 % and modulus of elasticity in not changed,
- fracture surfaces in both states were the transgranular ductile fracture with dimple morphology,
- after post-ECAP artificial aging increased tribological properties to abrasive wear by 33 %.

References

[1] L. Lodgaard, N. Ryum: Materials Science and Engineering, Vol. 283, 2000, p. 144-152, DOI:10.1016/S0921-5093(00)00734-6

[2] G. Mrówka-Nowotnik, J. Sieniawski: Journal of Materials Processing Technology, Vol. 161-163, 2005, p. 367-372, DOI:10.1016/j.jmatprotec.2005.02.115

[3] D. Jakubéczyová, M. Hagarová, J. Savková: Acta Metallurgica Slovaca, Vol. 18, 2012, No. 1, p. 13-19
[4] K. Fujita, T. Fujita, K. Oh-ishi, K. Kaneko, Z. Horita, T.G. Langdon: Materials Science Forum, Vol. 475-479, 2005, p. 4047-4050, DOI:10.4028/www.scientific.net/MSF.475-479.4047
[5] R. Hu et al.: Journal of Materials Science and Technology, Vol. 26, 2010, No. 3, p. 237-243, DOI:10.1016/S1005-0302(10)60040-0
[6] L. P. Borrego, L.M. Abreu, J. M. Costa, J. M. Ferreira: Engineering Failure Analysis, Vol. 11, 2004, p. 715-725, DOI:10.1016/j.engfailanal.2003.09.003
[7] S. J. Andersen et al.: Materials Science and Engineering, Vol. A390, 2005, No.127, p. 127-138, DOI:10.1016/j.msea.2004.09.019
[8] M. A. Van Huis, J. H. CHen, H. W. Zandbergen, M. H. F. Sluiter: Acta Materialia, Vol. 54, 2006, No. 11, p. 2945-2955, DOI:10.1016/j.actamat.2006.02.034
[9] G. Mrówka-Nowotnik, J. Sieniawski, A. Nowotnik: Journal of Achievements in Materials and Manufacturing Engineering, Vol. 32, 2009, No. 2, p. 162-170
[10] P. H. Ninive, O. M. Lřvvik, A. Strandlie: Metallurgical and Materials Transactions A, Vol. 45A, 2014, p. 2916-2924 DOI: 10.1007/s11661-014-2214-4
[11] R. Vissers, M. A. van Huis, J. Jansen, H. W. Zandbergen, C. D. Marioara, S.J. Andersen: Acta Materialia, Vol. 55, 2007, p. 3815–3823, DOI:10.1016/j.actamat.2007.02.032
[12] C. D. Marioara, H. Nordmark, S. J. Andersen, R. Holmestad: Journal of Materials Science, Vol. 41, 2006, p. 471-478, DOI:10.1007/s10853-005-2470-1
[13] L. Katgerman, D. Eskin: Hardening, Annealing, and Aging. In: Handbook of Aluminum, Physical Metallurgy and Processes, edited by G. E. Totten, D. S. MacKenzie, CRC Taylor and Francis, London, New York, 2003, p. 259-303
[14] W. F. Miao, D. E. Laughlin: Metallurgical and Materials Transactions A, Vol.31, 2000,No. 2, p. 361-371, DOI: 10.1007/s11661-000-0272-2
[15] K. Matsuda, D. Teguri, Y. Uetani, Y. Sato, S. Ikeno: Scripta Materialia, Vol. 47, 2002, No. 12, p. 833-837, DOI:10.1016/S1359-6462(02)00325-1
[16] M. Jin, J. Li, G. Shao: Materials Science Forum, Vol. 546-549, 2007, p. 825-828, DOI: 10.4028/www.scientific.net/MSF.546-549.825
[17] D. A. Little, et al.: Corrosion Science, Vol. 49, 2007, No. 2, p. 347-372, DOI:10.1016/j.corsci.2006.04.024
[18] P. Lacková, M. Hagarová, J. Cervová, I. Mamuzić: Acta Metallurgica Slovaca, Vol. 20, 2014, No. 2, p. 209-216, DOI:10.12776/ams.v20i2.283
[19] J. Bidulská, T. Kvačkaj, R. Bidulský, M. Actis Grande: Kovove Materialy, Vol. 46, 2008, No. 6, p. 339-344
[20] T. Kvačkaj, R. Bidulský (eds.): Aluminum Alloys, Theory and Applications, InTech, Rijeka, 2011, DOI: 10.5772/576
[21] T. Kvačkaj et al.: Archives of Metallurgy and Materials, Vol. 58, 2013, No. 2, p. 407-412, DOI: 10.2478/amm-2013-0008
[22] J. Bidulská et al.: Archives of Metallurgy and Materials, Vol. 58, 2013, No. 2, p. 371-375, DOI: 10.2478/amm-2013-0002
[23] R. Kočisko, R. Bidulský, L. Dragošek, M. Škrobian: Acta Metallurgica Slovaca, Vol. 20, 2014, No. 3, p. 302-308, DOI: 10.12776/ams.v20i3.366

[24] G. Y. Jin et al.: Materials Science and Engineering, Vol. A530, 2011, p. 462-468, DOI:10.1016/j.msea.2011.09.113
[25] M. Fujda et al.: Materiali in technologije, Vol. 46, 2012, No. 5, p. 465-469
[26] J. Bidulská et al.: Acta Metallurgica Slovaca, Vol. 16, 2010, No. 1, p. 4-11
[27] P. Lacková, O. Milkovič, M. Buršák, T. Kvačkaj: Key Engineering Materials, Vol. 635, 2015, p. 18-21, DOI:10.4028/www.scientific.net/KEM.635.18

Acknowledgment
This study was supported by the grant projects VEGA 1/0549/14.