Key Engineering Materials
ISSN: 1662-9809, Vol. 716, pp 55-62
doi:10.4028/www.scientific.net/KEM.716.55

Submitted: 2016-02-16
Revised: 2016-07-14
Accepted: 2016-07-14

Numerical Optimization and Practical Implementation of the Tube Extrusion Process of Mg Alloys with Micromechanical Analysis of the Final Product

Andrij Milenin[1,a], Piotr Kustra[1,b], Dorota Byrska-Wójcik[1,c], Bartłomiej Plonka[2,d], Veronika Petráňová[3,e], Vladimír Hrbek[3,f] and Jiří Němeček[3,g] *

[1]AGH Univeristy of Scince and Technology, Kraków, Poland
[2]Institute of Non-Ferrous Metals, Light Metals Division, Skawina, Poland
[3]Czech Technical University in Prague, Prague, Czech Republic

[a]milenin@agh.edu.pl, [b]pkustra@agh.edu.pl, [c]byrska@agh.edu.pl, [d]bplonka@imn.skawina.pl, [e]veronika.petranova@fsv.cvut.cz, [f]vladimir.hrbek@fsv.cvut.cz, [g]jiri.nemecek@fsv.cvut.cz

Keywords: Magnesium Alloys, Extrusion, Optimization, Microstructure, Nanoindentation

Abstract. The paper is devoted to the development of a process of tubes extrusion from MgCa08 magnesium alloy. For optimization of extrusion process the Qform software was used. The numerical model of flow stress and fracture criterion for MgCa08 were obtained based on tension/compression measurements performed in a universal testing machine Zwick Z250. Predictions of the flow stress and deformations were modeled as well as the ductility of material. The process was optimized according to the plasticity and temperature criterions. In the optimization process, temperature of the billet and the speed of extrusion were determined. Based on the optimal parameters the extrusion of tubes with external diameter of 5 mm was performed in the laboratory press. On top of the macroscopic testing and calculations, investigations of the material microstructure and the micromechanical behavior of the material after the extrusion were performed by a combination of SEM and nanoindentation analyses. Micromechanical properties of the alloy were detected with the aid of statistical nanoindentation. Samples were characterized in terms of their microstructural defects, distribution of elastic modulus and hardness. Good particle dispersion and homogeneous-like distribution of micromechanical properties was found showing the efficiency of the extrusion process.

Introduction

The numerical modeling is very important stage in designing of metallurgical processes such as extrusion. Examples of works relating to numerical simulation of extrusion process can be easily found in literature [1-3]. The most often method used for simulation of metallurgical processes is the Finite Element Method (FEM). There are a few commercial tools using FEM which allow to model the extrusion process. In works [4-6] the Extrusion3d software was used. An example of software dedicated particularly to extrusion process modeling is the Qform-Extrusion [7]. This program was used in works [6, 8-10] for optimization of extrusion of aluminum shapes. From available FEM software dedicated to modeling of extrusion Forge3 and Deform should also be mentioned.

The extrusion of MgCa08 magnesium alloys is considered in this paper. The MgCa08 alloy has a very low technological plasticity [11, 12]. Problems resulting from a low plasticity of the considered alloy can be overcome by using appropriate material models, which allow to predict the fracture, and additional fracture criteria in the optimization process. The yield stress model and the fracture criterion were implemented to Qform using the Lua language. Material properties used for the simulation were determined by compression and tension tests performed with Zwick Z250 machine. For optimization of the extrusion process a few FEM simulations in the Qform software for various process parameters were performed. The aim of the optimization was to choose appropriate values for extrusion velocity, billet and die temperatures. Finally, based on the simulation results the extrusion process was performed and the microstructure of the obtained tubes was examined.

The boundary problem solution and optimization technique

The FEM simulation of the extrusion process was done by using Qform software. The mathematical model of the process consists of the following equations:
equilibrium equations:

$$\sigma_{ij,i} = 0 , \tag{1}$$

compatibility condition:

$$\xi_{ij} = \frac{1}{2}\left(v_{i,j} + v_{j,i}\right) , \tag{2}$$

constitutive equations:

$$\sigma_{ij}^{`} = \frac{2\overline{\sigma}}{3\overline{\xi}}\xi_{ij} , \tag{3}$$

incompressibility equation:

$$v_{i,j} = 0 , \tag{4}$$

energy balance equation:

$$k\left(t_{,i}\right)_{,i} + \beta\overline{\sigma}\overline{\xi} = 0 , \tag{5}$$

yield stress model:

$$\overline{\sigma} = \overline{\sigma}\left(\varepsilon, \xi, t\right) , \tag{6}$$

where: σ_{ij} – stress tensor, ξ_{ij} – strain rate tensor, v_i – components of flow vector, $\sigma_{ij}^{`}$ – deviator of stress tensor, σ, ε, ξ – effective stress, effective strain and effective strain rate, t – temperature, β – heat generation efficiency ratio distortion that is commonly accepted within the limits β=0.9 - 0.95 and k – thermal conductivity.

Material model and fracture criterion

The flow stress model for MgCa08 magnesium alloy is described with Hansel-Spittel equation:

$$\overline{\sigma} = A\exp\left(-m_1 t\right)\overline{\varepsilon}^{m_2}\overline{\xi}^{m_3}\exp\left(\frac{m_4}{\overline{\varepsilon}}\right)\left(1+\overline{\varepsilon}\right)^{m_5 t}\exp\left(m_7\overline{\varepsilon}\right)\overline{\xi}^{m_8 t}t^{m_9} , \tag{7}$$

where: A, $m_1 - m_9$ – empirical parameters.

The fracture criterion is based on the value of a critical strain. As long as the strain is smaller than a critical strain the material can be deformed without cracking [13, 14]:

$$D = \frac{\overline{\varepsilon}}{\varepsilon_p\left(k_\sigma, t, \overline{\xi}\right)} < 1, \tag{8}$$

where: D – ductility function, ε_p – critical deformation function, k_σ – triaxiality factor defined as $\sigma_0 / \bar{\sigma}$, where σ_o is the mean stress.

The equation 8 is implemented as the following integral

$$D = \int_0^\tau \frac{\bar{\xi}}{\varepsilon_p\left(k_\sigma, t, \bar{\xi}\right)} d\tau \approx \sum_{m=1}^{m=m_\tau} \frac{\bar{\xi}^{(m)}}{\varepsilon_p\left(k_\sigma, t, \bar{\xi}\right)} \Delta\tau^{(m)} \tag{9}$$

where: τ – time of deformation, $\Delta\tau^{(m)}$ – time increment, $\bar{\xi}^{(m)}$ – the values of the strain rate in the current time, m – index number of time step during numerical integration along the flow line.

The critical strain is calculated from the following equation depending on values of the triaxiality factor, temperature and strain rate [14]:

$$\varepsilon_p(k_\sigma, t, \bar{\xi}) = d_1 \exp(-d_2 k_\sigma) \exp(d_3 t) \bar{\xi}^{d_4}, \tag{10}$$

where: d_1-d_4 – empirical coefficients.

An additional fracture criterion is considered in the form of temperature limit which must be lower than melting temperature (516 °C).

Macroscopic material tests

The flow stress and fracture parameters for MgCa08 (Mg 99.2 wt.%, Ca 0.8 wt.%) alloy were obtained by compression and tension tests performed in the Zwick Z250 machine at the AGH University of Science and Technology. Testing conditions were as follows: temperatures 250, 300, 400 °C, and two strain rates 0.1 and $1s^{-1}$ [15]. Results of the compression tests were used to determine the flow stress model and results of both tests were used for identification of the fracture (workability) model.

Flow stress model and ductility function

Empirical parameters of the flow stress model (Eq. 7) for MgCa08 magnesium alloy were determined by an inverse analysis. Following values were obtained: A = 405.85; m_1 = -0.00826428; m_2 = -0.0281807; m_3 = 0.020492; m_4 = -0.0114059; m_5 = 0.00521939; m_7 = -0.69316; m_8 = 0.0001636; m_9 = 0.192958.

The FEM simulations of all tensile and compression tests were performed and used in calculation of the fracture parameters (Eqs. 9 and 10). The aim of tests simulation was to obtain the conditions for $k, t, \bar{\xi}$ at the moment when the cracks initiated in the tests. Based on these results the following values of parameters d_1-d_4 were obtained: d_1 = 0.04611; d_2 = 0.4759; d_3 = 0.01265; d_4 = -0.07009.

Optimization of the extrusion process of MgCa08 tube

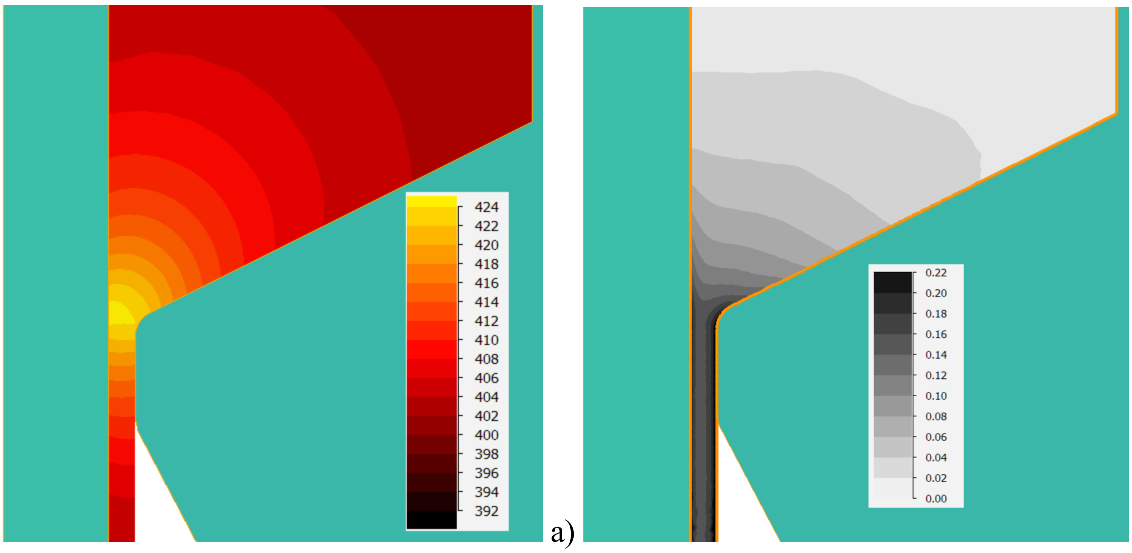
Optimization of the extrusion process was done using the Qform software.. A series of simulations were performed. A rod with diameter of 20 mm was used as a billet to extrusion process. In the extrusion process, an external diameter of tube was 5 mm and internal diameter was 4 mm. Numerical simulations were done for different billet temperatures and different extrusion velocities. Table 1 presents the boundary conditions and results for the four variants of simulation.

Table 1. Results of simulation of extrusion process (No. - number of the variant, V - extrusion velocity, t - temperature of the billet, t_{max} - maximum value of temperature in a billet during process, D - value of the fracture criterion, P – load).

No.	V [mm/s]	t [C]	t_{max} [C]	D [-]	P [kN]
1	1.0	400	450	0.30	260
2	1.0	350	403	0.54	300
3	0.5	400	424	0.31	240
4	0.5	350	375	0.36	250

It is clear from numerical simulations that the fracture criterion was not reached in all simulated variants. Additionally, the temperature did not reach the melting point. Based on the value of the parameter D and the extrusion force P variant No. 3 was selected as the best one for the extrusion process of proposed tubes.

Figure 1 presents distribution of the temperature and fracture parameters for variant No. 3. The maximum value of the fracture parameter reaches the value 0.31 but the scale in figure 1 is limited to value 0.22. The used scale makes the non-uniform distribution of the fracture criterion on the tube cross section more visible. The highest values of the fracture parameter are located at external and internal surfaces of the tube.



a) b)

Fig. 1. Results of simulation of the extrusion process of MgCa08 alloy for variant No. 3 : a) distribution of temperature °C, b) distribution of fracture parameter *D*.

Practical implementation

The experimental part of the extrusion process was carried out in the Institute of Non-Ferrous Metals in Skawina (Poland). Figure 2 shows schematically the extrusion setup with a die which includes a chamber designed to reduce the force during extrusion. The tubes were extruded using a rod with diameter 20 mm. Extrusion velocity was set as 0.5 mm/s and the temperature as 400 °C which corresponds to the variant No. 3 of numerical simulations. In this case it was possible to extrude the proper tube without defects. Extruded tubes are presented in Fig. 3.

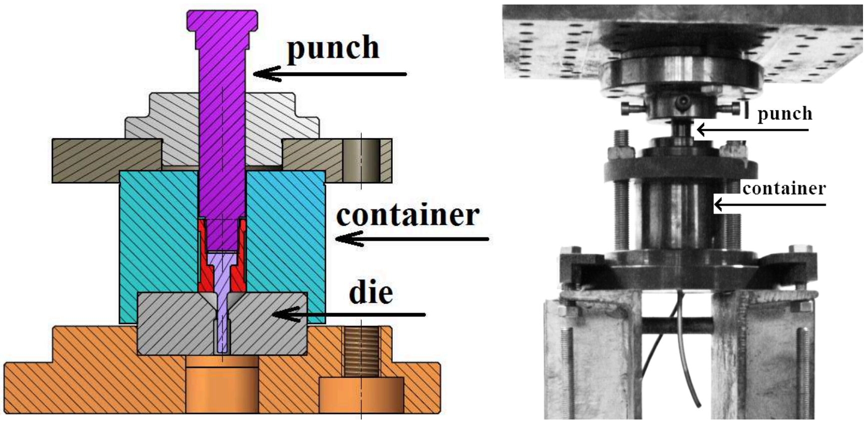


Fig. 2 Extrusion stand used for extrusion of tubes from MgCa08 alloy.

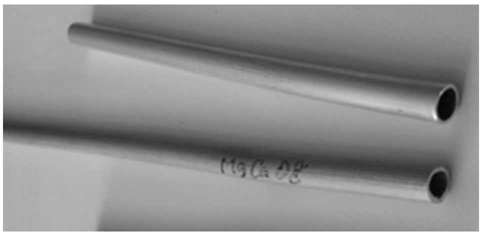


Fig. 3 Extruded tubes according to the variant No. 3 of numerical simulations.

Microstructural analysis of extruded MgCa08 tubes

As extruded MgCa08 tubes were taken for the analysis. The samples were fixed in an epoxy resin, cut and cross sections grinded and polished by a metallographic procedure with SiC papers. Careful procedure with low force needed to be applied since preparation of magnesium is rather difficult. During cutting, grinding, or handling, mechanical twinning may result, if pressures are excessive [16]. The final polishing step contained mechanical chemical polishing with 10-30 nm colloidal silica. The resulting sample surface roughness measured with AFM was RMS=26 nm on 50×50 μm area.

Scanning electron microscopy (SEM) was applied to characterize microstructural features occurring in the cross section and the check the surface quality. Fig. 4 shows MgCa08 sample composed of Mg matrix (large equiaxial grains that crystallize in hexagonal hcp lattice) with homogeneously dispersed particles of Ca (black dots with white surroundings in Fig. 4b). Low-alloyed Mg-Ca systems consist of α-phase solid solution (Mg with interstitial Ca) and eutectic structure (α-phase+Mg_2Ca) [17]. According to an image analysis, about 0.8 % volume is formed by calcium precipitates (black dots in Fig. 4b), another 0.8 % is composed of Mg_2Ca (white spots in Fig. 4b) and 98.4 % composes of Mg.

It can be seen in the SEM image taken inside the tube wall thickness (Fig. 4b) that the Ca precipitates are homogeneously dispersed within the Mg matrix showing indirectly the efficiency of the extrusion process. On the other hand, smaller magnification optical image (Fig. 4a) shows some unequal distribution of defects within the wall. More defects are located at interior and exterior sides of the wall. This finding corresponds with the evolution of the D parameter calculated earlier in the paper (see also Fig. 1b).

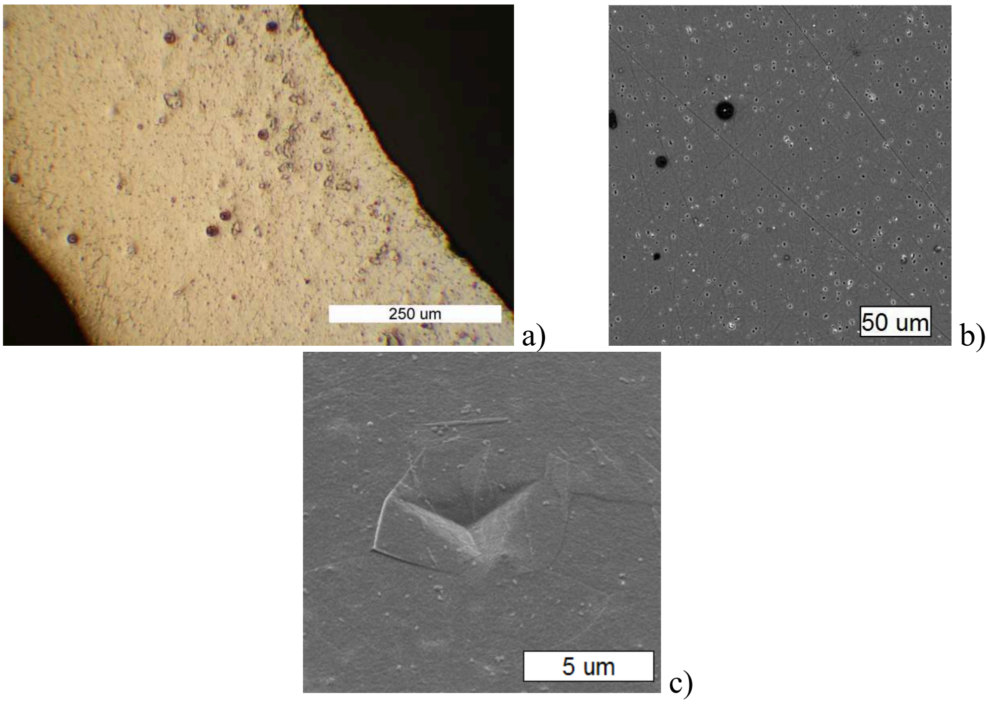


Fig. 4 (a) An optical image of the tube wall. (b) SEM image of MgCa08 microstructure inside the tube. (c) An indent performed in Mg matrix.

The in/homogeneity of the micromechanical properties was studied by means of statistical nanoindentation. Average tube wall mechanical properties were measured with Hysitron Tribolab® nanoindenter equipped with the Berkovich tip indenter. Several locations of the walls were tested to capture their heterogeneity and to capture all phases in a representative volume. The samples were covered by a series of 5×5 indents (Fig. 4c) with 10 µm spacing at several distant locations. Standard load controlled test for an individual indent consisted of three segments (loading, holding, unloading) lasting for 5 s each. Maximum applied load was set to 5 mN. Reduced elastic moduli (E_r) and hardness (H) were evaluated for each indent using standard Oliver and Pharr methodology [18].

Intact Mg-matrix areas (out of the pores) show relatively homogeneous value of E_r=39.45±1.79 GPa (Fig. 5) and H=0.58±0.05 GPa which matches well with the literature values for pure Mg. The addition of 0.8 wt% of Ca into the Mg matrix affects only the intimate surroundings of the Ca precipitates as can be seen in Fig. 4b. The mechanical performance of the prevailing Mg matrix (in terms of E_r and H) remains unaffected.

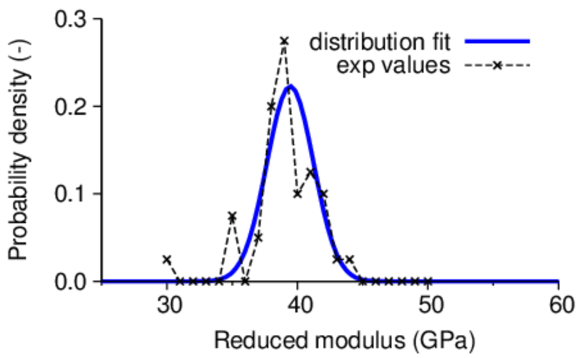


Fig. 5 Distribution of reduced moduli measured by nanoindentation in random locations.

Conclusions

The numerical model of the tube extrusion process of MgCa08 alloy was developed in this paper. The simulations were performed with the Qform software. The Hansel-Spittel equation was used as the material model and the fracture criterion based on the value of a critical strain was implemented into the Qform software. Based on results of simulation optimal parameters of the extrusion process were chosen and the tube extrusion was carried out. After the extrusion microstructure and micromechanical properties of obtained tubes were studied. The distribution of elastic moduli and hardness is homogeneous inside the tube wall. Based on optical analysis the microstructure of extruded tubes showed that more defects are located at interior and exterior sides of the tube which agrees with results of the simulation where values of the fracture parameter D tend to be higher in the same area.

Acknowledgements

Financial support of the Ministry of Education, Youth and Sports of the Czech Republic (Project No. 8F15004) and of the National Centre of the Research and Development of the Poland (Project title: Multi scale model of the laser dieless drawing process of tubes from hardly deformable magnesium alloys, Project acronym: MgTubeDieLess, Visegrad Group (V4)-Japan Joint Research Program on Advanced Materials) is gratefully acknowledged.

References

[1] P. Machado, Extrusion die design, Proceeding of Fifth International Extrusion Technology Seminar, Chicago, USA, May 19-22, 1992, pp. 385-389.

[2] M. Kiuchi, J. Yanagimoto, V. Mendoza, Three-Dimensional FE Simulation and Extrusion Die Design, J. Jpn. Soc. Technol. Plast. 39 (1998) 27-32.

[3] J. Herberg, K. Gundeso, I. Skauvic, Application of Numerical Simulation in Design of Extrusion Dies, 6th Int. Aluminium Extrusion Technology Seminar, Chicago, USA, May 14-17, 1996, pp. 275-281.

[4] A. Milenin, Mathematical Modeling of Operations of Correcting the Dies for Section Extruding, Metallurgicheskaya i Gornorudnaya Promyshlennost 1-2 (2000), 64-66.

[5] A. Milenin, S. Berski, G. Banaszek, H. Dyja, Theoretical Analysis and Optimization of Parameters in Extrusion Process of Explosive Cladded Bimetallic Rods, J. Mater. Process. Tech. 157-158 (2004) 208-212.

[6] A.I. Lishnij, N.V. Biba A. Milenin, Two Levels Approach to the Problem of Extrusion Optimization, Simulation of Materials Processing: Theory, Methods and Applications, in: J. Huetink, F.P.T. Baaijens, (Eds.), Proc. of the 7th Int. Conf. on Numerical Methods in Industrial Forming Processes, Enschede, Netherlands, 1998, pp. 627–631.

[7] N. Biba, S. Stebunov, A. Lishny, A. Vlasov, New Approach to 3D Finite-Element Simulation of Material Flow and its Application to Bulk Metal Forming, 7th International Conference on Technology of Plasticity, Yokohama, Japan, Oct 27 – Nov 1, 2002, pp. 829-834.

[8] A. Milenin, Modelowanie Numeryczne Procesów Wyciskania Profili z Zastosowaniem Gęstości Dyslokacji jako Zmiennej Wewnętrznej w Modelu Reologicznym Materiału, Informatyka w Technologii Materiałów 1(2) (2002) 26-33.

[9] A. Milenin, N. Biba, S. Stebunow, Modelowania Procesów Wyciskania Cienkościennych Kształtów z Wykorzystaniem Teorii Dyslokacji do Opisania Właściwości Reologicznych Stopów Aluminium, Materiały 9 Konferencji Informatyka w Technologii Metali, Jan 13 – 16, 2002, pp. 217-222.

[10] A. Milenin, A.N. Golovko I. Mamuzic, The Application of Three-Dimensional Computer Simulation when Developing Dies for Extrusion of Aluminium Shapes, Metallurgija 41(1) (2002) 53-55.

[11] N. Odawa, M. Shiomi, K. Osakada, Forming Limit of Magnesium Alloy at Elevated Temperatures for Precision Forming, Int. J. Mach. Tools Man. 42 (2002) 607-614.

[12] K. Yoshida, Cold Drawing of Magnesium Alloy Wire and Fabrication of Microscrews, Steel Grips. 2 (2004) 199-202.

[13] P. Kustra, A. Milenin, B. Płonka, T. Furushima, Production Process of Biocompatible Magnesium Alloy Tubes Using Extrusion and Dieless Drawing Processes, J. Mater. Eng. Perf. 25(6) (2016) 2528–2535.

[14] A. Milenin, P. Kustra, D. Byrska-Wojcik, FEM-BEM code for the multiscale modeling and computer aided design of wire drawing technology for magnesium alloys, Adv. Eng. Mater. 16 (2014) 202–210.

[15] A. Milenin, M. Gzyl, T. Rec, B. Plonka Computer aided design of wires extrusion from biocompatible Mg-Ca magnesium alloy, Archives of Metallurgy and Materials, 59(2) (2014) 551–556.

[16] G.V. Voort, Metallography of Magnesium and its Alloys, Tech Notes 4(2), publ. Buehler, 1997.

[17] M.M. Avedesian, H. Baker, Mg and Mg Alloys. ASM International. Materials Park OH, 1999.

[18] W. Oliver, G. Pharr, An Improved Technique for Determining Hardness and Elastic-Modulus using Load and Displacement Sensing Indentation Experiments, J. Mater. Res. 7 (1992) 1564-1583.