

Improvement of Mechanical Properties for EN AW 6082 Aluminium Alloy Using Equal-Channel Angular Pressing (ECAP) and Post-ECAP Aging

Martin FUJDA¹, Tibor KVAČKAJ², Katarína NAGYOVÁ¹

¹*Department of Materials Science, Faculty of Metallurgy,
Technical University of Košice, Slovak Republic*

²*Department of Metal Forming, Faculty of Metallurgy,
Technical University of Košice, Slovak Republic*

Received Apr. 8, 2008

Accepted May. 16, 2008

Abstract

The mechanical properties and microstructure of EN AW 6082 aluminium alloy subjected to severe plastic deformation and aging treatment were compared with those of the extruded and artificially aged state (initial state). The initial state of alloy subjected to solution annealing and quenching was severely deformed at ambient temperature by equal channel angular pressing (ECAP) following route C up to three passes. Polyedric microstructure of initial state was considerably changed by the repetitive ECA-pressing. Deformation bands with different density of slip lines were observed in microstructure of ECAPed and aged states, which indicated non-uniform deformation across the cross-section of ECAPed specimens. The high strength of ECAPed states was the result of the strain hardening of alloy. Application of the artificial aging treatment after the severe plastic deformation of analyzed alloy in the ECAP die improves the ductility and the strength of EN AW 6082 aluminium alloy. This was due to that the hardening effect by expected sequence Mg₂Si-precipitation dominates the softening effect by microstructure with low recovery and relaxation of internal stress during aging treatment. The reason of low notch toughness of ECAPed and aged alloy is due to the intensive and heterogeneous strain hardening of alloy during ECA-pressing. A moderate improvement of notch toughness was induced by application of the artificial aging treatment for ECAPed alloy state instead of the natural aging.

Key words : EN AW 6082 aluminium alloy, ECAP, strength, tensile ductility, notch toughness heterogeneous microstructure, strain hardening

Introduction

Equal-Channel Angular Pressing (ECAP) is a very useful method for producing ultra-fine microstructures of Al-based alloys with significantly improved mechanical properties.⁽¹⁻⁵⁾ In addition, some ultra-fine grained Al-based alloys produced by ECAP procedure showed a superplastic forming capability.⁽⁵⁻¹⁰⁾ Severe plastic deformation by the ECAP process also increases markedly the density of lattice defects in the solid solution of Al-based alloy and thus can accelerated the precipitation process of strengthening particles during the post-ECAP aging treatment applied for the age-hardenable alloy.⁽¹¹⁻¹³⁾

ECAP technology has been used frequently in researches of micro the severe plastic deformation effect on the structure and properties of the age-hardenable AlMgSi alloys and recently mainly

high-strength EN AW 6061 and 6082 alloys.^(4, 14-19) These high-strength AlMgSi alloys are suitable for different miscellaneous structural applications in the building, automotive and aircraft industries, due to their strong modification of strength induced by precipitation phenomena which is accompanied by a low density, good corrosion properties and good weldability. Optimal combination of heat treatment (solution annealing and artificial aging) and severe plastic deformation by the ECAP procedure enabled to achieve a significant increase in alloy strength by refinement of the solid solution grains with high dislocation density in combination with strengthening precipitation of β' -Mg₂Si phase particles during a post-ECAP aging treatment.

The aim of the present work is to investigate the effect of severe plastic deformation by the ECAP process and subsequent aging treatment on mechanical properties of EN AW 6082 aluminium alloy.

Materials and Experimental

The experiments were carried out on the EN AW 6082 aluminium alloy, the chemical composition of which is presented in Table 1.

Table 1. Chemical composition (wt.%) of the investigated EN AW 6082 aluminium alloy

| Mg | Si | Mn | Fe | Cr | Zn | Cu | Al |
|------|------|------|------|------|------|------|------|
| 0.87 | 0.90 | 0.85 | 0.19 | 0.09 | 0.03 | 0.08 | Bal. |

Analyzed alloy in the form of extruded rods subjected to artificial aging was used as the initial state (IS). Prior to deformation in an ECAP die, specimens of the initial state were solution annealed at 550°C (holding time 1.5 h), and cooled to the ambient temperature by water quenching. The quenched specimens were then subjected to deformation in an ECAP die having a channel intersection angle $\Phi = 90^\circ$ and arc of curvature $\Psi = 37^\circ$. Pressing of specimens of size $\varnothing 10$ mm x 80 mm in the ECAP die was realized at ambient temperature by route C (turning the specimen by 180°) up to three passes corresponding to deformation ratio $\varphi = 3, 5$ ^(14 and 20). After severe deformation the specimen was subjected to natural aging for 800 h, or to artificial aging at 100°C as a function of time to determine the optimum post-ECAP artificial aging condition.

Microstructure characteristics of the initial state of the investigated alloy, its state after quenching, deformation in the ECAP die and subsequent ageing treatment were analyzed in the central zone of the specimen's cross-section using a light microscope. Microstructures were prepared by common metallographic methods (special enhanced etching – etchant: modified Kroll).

The influence of the applied heat treatment, severe plastic deformation by ECAP process and natural or artificial aging on the mechanical properties of the analyzed alloy was evaluated by tensile test, Vickers hardness measurement (HV 10) and impact test. The tensile test (deformation rate $2.5 \times 10^{-4} \text{ s}^{-1}$) was carried out on short specimens made from ECAP processed billet by machining along the longitudinal direction (Figure 1). Subsequently, characteristics of the strength (yield stress: 0.2%YS; ultimate tensile strength: UTS), elongation (El.) and reduction in area (Re.) were determined. Impact toughness test samples were also made from ECAP processed billet

by machining along the longitudinal direction. The size of the test pieces was 8 mm x 4 mm in cross-section and 55 mm in length, with a V-notch 1 mm in width and 1 mm in depth. Charpy impact test machine was used for measuring the absorbed energy of the samples as the notch toughness at ambient temperature.

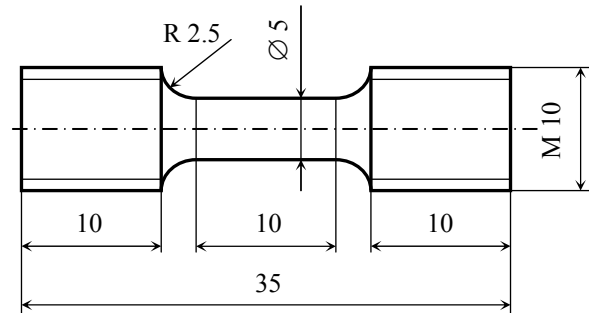


Figure 1. The shape and parameters short specimen for the tensile test

Results and Discussion

Hardness

The hardness of analyzed alloy states is summarized in Table 2. Figure 2 shows the variation of Vickers hardness of the ECAPed analyzed alloy as a function of artificial aging time at temperature 100°C. A significant increase in hardness value (by about 97%) is accomplished after the ECA-pressing of the analyzed alloy quenched condition. A post-ECAP natural or artificial aging treatment was applied to increase the strength of ECAPed alloy. The ECAPed samples reached the peak hardness after ~ 30 h of artificial aging at 100°C. Hardness of ECAPed alloy gradually increases with artificial aging time from 0 to 30 h. The maximum hardness of the ECAPed and artificially aged (30 h at 100°C) condition of the analyzed alloy is about ~ 41% higher, comparing with the hardness of the industrially processed initial state of analyzed EN AW 6082 aluminium alloy. This artificial aging time (30 h at 100°C) was selected to obtain expected optimum strength of the ECAPed analyzed alloy.

Table 2. Hardness of analyzed alloy states

| alloy state | HV 10 |
|--------------------------------------|-------|
| initial | 100.2 |
| quenched | 66.1 |
| ECAPed | 130.3 |
| ECAPed+naturally aged (800h) | 139.5 |
| ECAPed+artificially aged (30h/100°C) | 141.7 |

Improvement of Mechanical Properties for EN AW 6082 Aluminium Alloy Using Equal-Channel Angular Pressing (ECAP) and Post-ECAP Aging

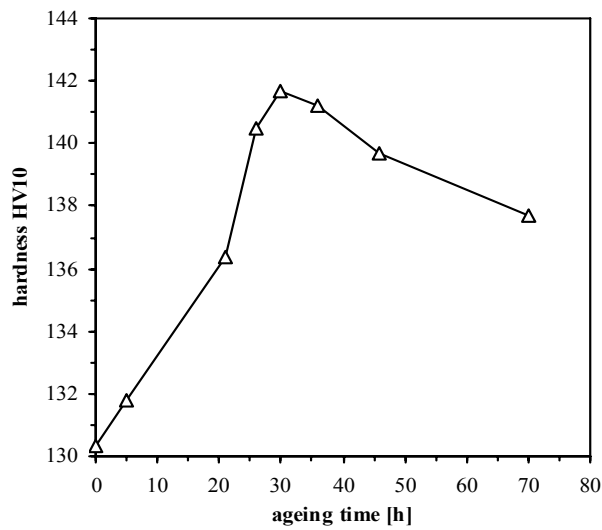


Figure 2. Vickers hardness of the ECAPed analyzed alloy as a function of artificial aging time at 100°C

Microstructure

Initially recrystallized polyedric microstructure of the analyzed alloy with grain size about 6 μm is shown in Figure 3. A presence of irregular intermetallic particles of Al(FeMn)Si phase, undissolved Mg_2Si particles and fine Mn-rich dispersive particles⁽²¹⁾ was also observed in the initial state's microstructure. The role of Mn-rich dispersoids is to prevent the solid solution grains growth of Al-based alloy.⁽²²⁾ Negligible growth of equiaxed grains of solid solution to 7.3 μm was confirmed after solution annealing and quenching of alloy initial state.⁽²³⁾ Any considerable increase in the grains size was prevented by fine dispersed Mn-rich particles, which inhibited of recrystallization process.⁽²⁰⁾

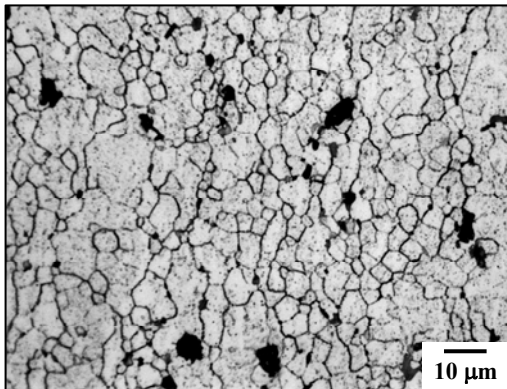


Figure 3. Microstructure of alloy initial state

The repetitive ECA-pressing of quenched alloy condition induced a significant change of the quenched polyedric microstructure⁽²³⁾ as shown in Figure 4. Heterogeneous deformed microstructure of the ECAPed and aged alloy indicates a non-uniform deformation across the cross-section of the ECAPed specimen. No difference was observed between microstructure of the ECAPed condition after the natural (800 h) or artificial aging (30h/100°C) using a light microscope.

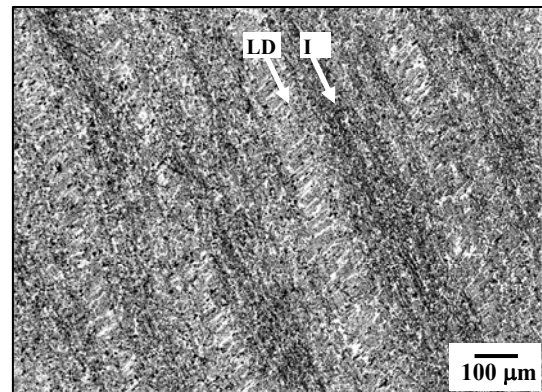


Figure 4. Microstructure of the ECAPed and naturally aged alloy condition
ID – an intensively deformed region
LD – a less deformed region

Figures 5 and 6 show a different microstructure of ECAPed and artificially aged alloy condition in the intensively (ID) and less (LD) deformed region, respectively. High density of slip lines is characteristic for the intensively deformed region of microstructure. On the other hand, in the adjacent less deformed region of microstructure, the lower density of slip lines across the columnar grains was observed.

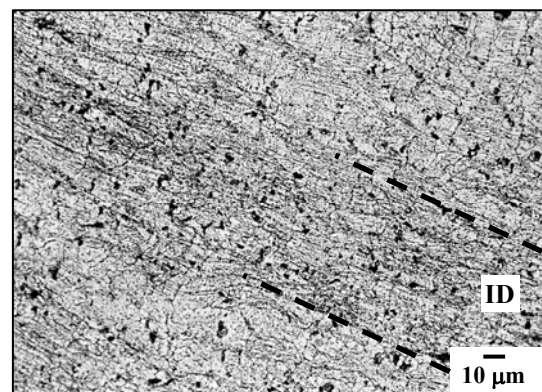


Figure 5 Microstructure of ECAPed and artificially aged alloy in the intensively deformed band (ID)

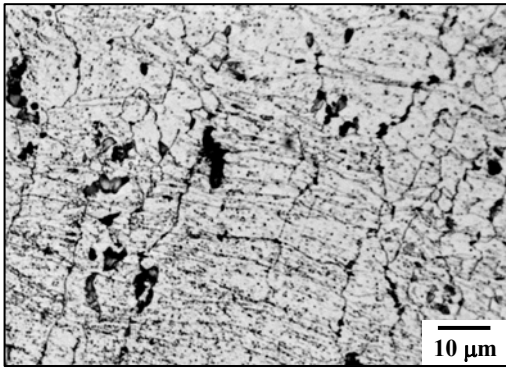


Figure 6. Microstructure of ECAPed and artificially aged alloy in the less deformed region

Tensile Testing

A comparison of mechanical properties determined for industrially processed (initial state) or severely deformed and aged EN AW 6082 aluminium alloy is provided by the values of strength and tensile ductility, which are presented in Table 3. The tensile stress-strain curves of analyzed alloy states are shown in Figure 7.

Table 3. Mechanical properties of analyzed alloy states

| alloy state | 0.2% YS [MPa] | UTS [MPa] | El. [%] | Re. [%] |
|---------------------------|---------------|-----------|---------|---------|
| initial state | 340 | 385 | 19.6 | 38.6 |
| ECAPed+ naturally aged | 407 | 418 | 13.0 | 18.2 |
| ECAPed+ artificially aged | 408 | 427 | 20.1 | 29.3 |

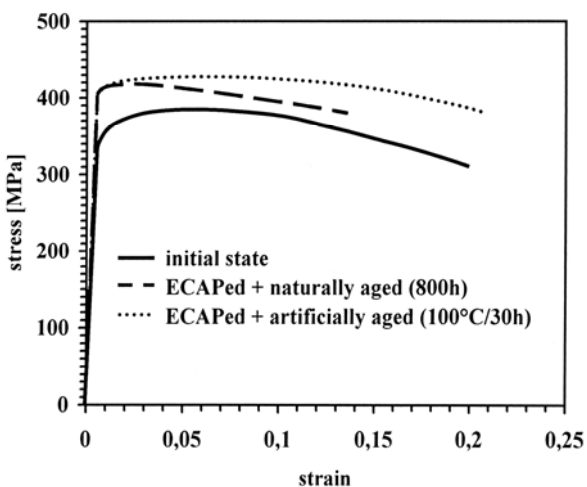


Figure 7. Tensile stress-strain curves for the analyzed states of investigated aluminium alloy

Yield stress and ultimate tensile strength of the ECAPed and naturally aged (800h) alloy are higher (0.2% YS: +19.7 %; UTS: + 8.6%) than those of the industrially processed initial state (extruded and artificially aged) of analyzed alloy. but the tensile ductility of ECAPed and naturally aged alloy is lower (El.: -6.6%; Re.: - 20.4%).⁽²³⁾ However, the ECAPed and artificially aged alloy (30h at 100°C) is even notably stronger (UTS: + 2.2 %) than the naturally aged alloy after the repetitive ECA-pressing. In addition, when the artificial aging of ECAPed alloy replaced the natural aging, the tensile elongation is improved from 13 % to 20.1%. This increased value of the tensile elongation is even little higher than that obtained from initial state of analyzed alloy. The increase in strength of the ECAPed and naturally aged alloy was first of all the consequence of the more expressive strain hardening of the solid solution by the ECAP process at ambient temperature in comparison with the conventional process of hot extrusion and artificial aging. The application of artificial aging treatment after severe plastic deformation of alloy in the ECAP die improves the ductility and also the strength of EN AW 6082 aluminium alloy because the hardening effect by the expected sequence Mg₂Si-precipitation dominates the softening effect by microstructure with low recovery and relaxation of internal stress.^(11 and 19) This statement is also confirmed by comparison of the tensile stress - strain curves obtained from initial and ECAPed states (Figure 5) which show, higher uniform deformation during tensile tests of specimens prepared from the initial or ECAPed and artificially aged state of analyzed alloy in comparison with that obtained from the specimens subjected to severe plastic deformation in the ECAP die and natural aging.

Impact Testing

Values of the absorbed energy during impact test of the analyzed alloy states are summarized in Table 4. The absorbed energy of the initial state samples of alloy is 25.1 J.cm⁻². Impact testing of quenched samples was carried out immediately after the solution treatment of initial state and quenching. In this case, the dissolution of Mg₂Si-precipitates takes place during the solution treatment and the precipitation of the strengthening phases (GP - zones, β', β) before impact testing can be ignored. Therefore, the absorbed energy of quenched state is relatively high (54.8 J.cm⁻²).

Table 4. The absorbed energy by Charpy impact test of the analyzed alloy states

| alloy state | absorbed energy [J.cm ⁻²] |
|----------------------------|--|
| initial state | 25.1 |
| quenched | 54.8* |
| ECAPed + naturally aged | 12.5 |
| ECAPed + artificially aged | 16.5 |

*incomplete breakage of specimen

After the repetitive ECA-pressing and the subsequent natural aging treatment of alloy, the absorbed energy decreased markedly reaching 12.5 J.cm⁻². This value is about 2 times lower than that of the industrially processed (initial state) analyzed alloy. The reason of this toughness loss is first of all the intensive and heterogeneous strain hardening of analyzed alloy during the severe plastic deformation in the ECAP die. A moderate improvement of the notch toughness was induced by the application of artificial aging treatment for ECAPed alloy state instead of natural aging. This phenomenon can be outlined by the low recovery of severe deformed alloy microstructure and relaxation of internal stress during artificial aging, which also improved the strength and elongation during tensile testing. Of course, the coarse irregular multicomponent intermetallic particles, dispersive particles and the assumed precipitates of strengthening phase have also some detrimental effect on the notch toughness of the ECAPed and aged EN AW 6082 Al alloy.

Conclusion

The severe plastic deformation ($\phi = 3.5$) of the solution annealed EN AW 6082 aluminium alloy by the ECAP process resulted in considerable but non-uniform deformation of the solid solution at the microscopic scale. The increase in strength and hardness and, on the other hand, the decrease in tensile ductility of ECAPed and aged alloy resulted from the more intensive strain hardening of the solid solution by the ECAP process and natural aging treatment in comparison with the conventional process of extrusion and subsequent artificial aging of the investigated EN AW 6082 aluminium alloy.

When severe plastic deformation is combined with optimal artificial aging treatment at 100°C (30h), the further increase in hardness and ultimate tensile strength of the ECAPed state is obtained in comparison with the properties of ECAPed state after natural aging. The artificial ageing is also effective in improving the ECAPed state's tensile ductility in a consequence of the low recovery of ECAPed alloy and relaxation of internal stress.

After the repetitive ECA-pressing and the subsequent natural ageing treatment of EN AW 6082 aluminium alloy quenched state, the notch toughness of alloy decreased markedly. The reason of the notch toughness loss is first of all the intensive and heterogeneous strain hardening of analyzed alloy during the repetitive ECA-pressing. A moderate improvement of the notch toughness was induced by the application of artificial ageing treatment for ECAPed alloy state instead of natural ageing.

Acknowledgment

This work was supported by the Scientific Grant Agency of Slovak republic as grant project No. 1/3217/06 and by the Slovak Research and Development Agency as project APVV-20-027205.

References

- 1 Segal, V.M., Reznikov, V.I., Drobyshevskiy, A.E. and Kopylov, V.I. 1981. Plastic working of metals by simple shear. *Russ. Metall.* **1**: 99 – 105.
2. Furukawa, M., Horita, Z., Nemoto, M. and Langdon, T.G. 2001. Review: Processing of metals by equal-channel angular pressing. *J. Mater. Sci.* **36**: 2835 – 2843.
3. Furukawa, M., Horita, Z. and Langdon, T.G. 2001. Developing Ultrafine Grain Sizes Using Severe Plastic Deformation. *Adv. Eng. Mater.* **3**: 121 – 125.
4. Horita, Z., Fujinami, T., Nemoto, M. and Langdon, T.G. 2001. Improvement of mechanical properties for Al alloys using equal-channel angular pressing, *J. Mater. Process. Technol.* **117**: 288 – 292.

5. Islamgaliev, R.K., Yunusova, N.F., Valiev, R.Z., Tsenev, N.K., Perevezentsev, V.N. and Langdon, T.G. 2003. Characteristics of superplasticity in an ultrafine-grained aluminum alloy processed by ECA pressing. *Scr. Mater.* **49** : 467 – 472.
6. Lee, S., Furukawa, M., Horita, Z. and Langdon, T.G. 2003. Developing a superplastic forming capability in a commercial aluminum alloy without scandium or zirconium additions. *Mater. Sci. Eng.* **A342** : 294 – 301.
7. Nemoto, M., Horita, Z., Furukawa, M. and Langdon, T.G. 1999. Microstructural Evolution for Superplasticity Using Equal-Channel Angular Pressing. *Mater. Sci. Forum.* **304 – 306** : 59 – 66.
8. Horita, Z., Lee, S., Ota, S., Neishi, K. and Langdon, T.G. 2001. Equal-Channel Angular Pressing as a Production Tool for Superplastic Materials. *Mater. Sci. Forum.* **357 – 359** : 471 – 476.
9. Xu, C., Furukawa, M., Horita, Z. and Langdon, T.G. 2003. Achieving a Superplastic Forming Capability thorough Severe Plastic Deformation. *Adv. Eng. Mater.* **5** : 359 – 364.
10. Starink, M.J., Gao, N., Furukawa, M., Horita, Z., Xu, C. and Langdon, T.G. 2004. Microstructural Developments in a Spray-Cast Al-7034 Alloy Processed by Equal-Channel Angular Pressing. *Rev. Adv. Mater. Sci.* **7** : 1 – 12.
11. Kim, W.J., Chung, C.S., Ma, D.S., Hong, S.I. and Kim, H.K. 2003. Optimization of strength and ductility of 2024 Al by equal channel angular pressing (ECAP) and post-ECAP aging. *Scr. Mater.* **49** : 333 – 338.
12. Murashkin, M.Y., Markushev, M.V., Ivanisenko, Y.V. and Valiev, R.Z. 2006. Strength of Commercial Aluminum Alloys after Equal Channel Angular Pressing and Post-ECAP Processing. *Solid State Phenomena.* **114** : 91 – 96.
13. Jong Kap Kim and Woo Jin Kima. 2007. Effect of Post-ECAP Aging on Mechanical Properties of Age-Hardenable Aluminum Alloys. *Solid State Phenomena.* **124 – 126** : 1437 – 1440.
14. Zrník, J., Nový, Z., Kvačkaj, T., Bernášek, V., Kešner, D. and Slámová, M. 2004. Vplyv technológií tvárnenia na vývoj štruktúry a vlastností AlMgSi zliatiny. *Acta Metall. Slovaca.* **10** : 277 – 284.
15. Cherukuri, B., Nedkova, T. S. and Srinivasan, R. 2005. A comparison of the properties of SPD-processed AA-6061 by equal-channel angular pressing, multi-axial compressions/ forgings and accumulative roll bonding. *Mater. Sci. Eng.* **A410 – 411** : 394 – 397.
16. Werenskiold, J.C. and Roven, H.J. 2005. Microstructure and texture evolution during ECAP of an AlMgSi alloy: Observations, mechanisms and modeling. *Mater. Sci. Eng.* **A 410 – 411** : 174 – 177.
17. Roven, H.J., Nesboe, H., Werenskiold, J.C. and Seibert T. 2005. Mechanical properties of aluminium alloys processed by SPD: Comparison of different alloy systems and possible product areas. *Mater. Sci. Eng.* **A410 – 411** : 426 – 429.
18. Leo, P., Cerri, E., De Marco, P.P., and Roven H.J. 2007. Properties and deformation behaviour of severe plastic deformed aluminium alloys. *J. Mater. Process. Technol.* **182** : 207 – 214.
19. Kim, W.J. and Wang, J.Y. 2007. Microstructure of the post-ECAP aging processed 6061 Al alloys. *Mater. Sci. Eng.* **A464** : 23 – 27.
20. Iwahashi, Y., Wang, J., Horita, Z., Nemoto, M. and Langdon, T.G. 1996. Principle of equal-channel angular pressing for the processing of ultra-fine grained materials. *Scripta Mater.* **35** : 143 – 146.
21. Fujda, M. and Vojtko, M. 2007. The effect of heat treatment condition on the microstructure and mechanical properties of EN AW 6082 aluminium alloy. *Acta Metall. Slovaca.* **S11. 13** : 585 – 591.

Improvement of Mechanical Properties for EN AW 6082 Aluminium Alloy Using Equal-Channel Angular Pressing (ECAP) and Post-ECAP Aging

22. Parson, N., Hankin, J., Hicklin, K. and Jowett, C. 2000. Comparison of the extrusion performance and product characteristics of three structural extrusion alloys: AA6061, AA6082 and AA6005A. In : *Proceedings of the 7th International Aluminum Extrusion Technology Seminar. vol. 1.* Washington. Aluminum Association : 1 – 12.
23. Fujda M., and Kvačkaj, T. 2007. Microstructure and Mechanical Properties of EN AW 6082 Aluminium Alloy Prepared by Equal-Channel Angular Pressing. *J. Met. Mater. Miner.* **17(2)** : 23 – 27.