ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 23, No. 1. 2017

Investigating Corrosion, Wear Resistance and Friction of AA5454-O Series after its Severe Deformation by Rolling

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crossref http://dx.doi.org/10.5755/j01.ms.23.1.14650

Received 11 April 2016; accepted 04 November 2016

AA5454-O is an easily wrought, or in other words, a ductile aluminium alloy, however, its mechanical properties are inferior as compared to those of other alloys. The change taking place in corrosion resistance of AA5454-O alloy as a result of its severe plastic deformation (SPD) by rolling has been investigated in this study. It has been observed that significant changes occurred in abrasion wear and corrosion resistances of AA5454-O alloy, which was severely deformed up to 80 % by rolling process. Corrosion resistance of the alloy that was severely deformed by rolling has increased. The effect of deformation rate on corrosion has been investigated by applying potentiodynamic test whereas on the other hand such change has been evidenced also through corrosion test. It has been observed that friction coefficient of severely deformed AA5454-O alloy varied by around 10 %, and that, associated with such change, its wear resistance also increased considerably. It has been determined that, as a result of severe deformation by rolling, hardness values rose in areas where the alloy was in contact with rolling surface. In this study, wear resistance of severely deformed alloy has been investigated as well. It has been observed that deformation value contributed positively to the increase in wear resistance.

Keywords: rolling, aluminium, plastic deformation, corrosion, wear, friction.

1. INTRODUCTION

Aluminium, a major characteristic of which is corrosion resistance, is being widely used in automotive, space research and marine industries because of this property. Aluminium 5454-O alloy is so important for corrosion, wear and it has got good resistance, in particular to seawater and general environmental conditions. It can be used for road transport body-building, chemical and process plant, marine, pressure vessels, containers, boilers. Because of this reason, it is very important to use it. Furthermore, before using it, it is made by rolling process for making sheets.

Apart from that, its thermal behaviour is of great significance in regard to use of other aluminium alloys. In addition, aluminium is preferred in the case of multiple plastic deformation processes due to its capability to form nano-structures. Al5454-O series has until now been subjected to ECAP (equal-channel angular pressing) or other multiple plastic deformation processes [1]. Rolling occupies an important place in ECAP processes in terms of changing the microstructure [2]. Previously researchers have in many cases noticed that severe plastic deformation (SPD) method changed tensile strength as well as toughness, wear and fatigue resistances [3 – 8]. Darmiani *et al.* have investigated that one of the most important factors is corrosion resistance [9]. Research has shown that increased repetition of rolling process decreases pitting or dimpling occurring in microstructure of the material. Processing of commercially pure titanium by application of high pressure torsion has changed corrosion resistance [10]. This situation indicates that there exists a significant relationship between grain improvement (refinement) and corrosion resistance [11]. ECAP process applied on microstructure has demonstrated that corrosion is of major importance not only in the case of Al but also in the case of stainless steel (304). In addition to that, microstructure and corrosion resistance of copper with or without SPD have been studied as well. In terms of corrosion resistance, microstructure of copper with SPD has been found very high as compared to that of copper without SPD [12]. As regards corrosion behaviour of Al-Si alloys (hyper-elastic), effectiveness of adhesion force and corrosion behaviour have been enhanced by means of SPD. In many further studies, impact of SPD on corrosion has been investigated [13]. Mechanical properties of Al-Ni alloys have been improved thanks to SPD method. Besides, significant changes have occurred in corrosion behaviour of commercially pure titanium after it was processed by application of SPD [14, 15]. It has been reported that mechanical properties of AZ31 magnesium alloys improved as well following their treatment with SPD [16]. By addition of Sc versus Zr, effects of Al-Zn-Mg-Cu alloys on corrosion resistance have been studied too [17, 18]. Furthermore, impact occurring in the course of time on protective coatings of mechanical alloys is also being studied [6]. Hot rolling also exerts significant effects on mechanical behaviour of materials. Since this process may at the same time be regarded as an SPD procedure, it changes corrosion behaviour at a considerable level [12, 13]. It has not been possible to completely explain how the corrosion mechanism changed. Moreover, resistance of grains to corrosion behaviour in Hank solution could not be explained fully. For this reason, studies concerned with corrosion behaviour of alloys containing Mg have become increasingly important.

AA5454-O is an easily wrought, or in other words, a ductile aluminium alloy, however, its mechanical

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properties are inferior as compared to those of other aluminium alloys. Improving corrosion and abrasion wear resistances of AA5454-O alloy, which are likely to occur especially after plastic forming, is quite important in respect of the fabricated product's life at the place of use. If this alloy is compared with other aluminium alloys, its superior features over those of other alloys may be enumerated as follows: higher elongation after the application of tempering or heat treatment processes, higher elongation at rupture as a result of its deformation by rolling, and high corrosion resistance due to its being an aluminium alloy.

Although this alloy is being widely used in the commercial market, its corrosion, hardness and abrasion wear characteristics in the case of manufacturing under severe deformation conditions have not been researched yet. That is why this study has been undertaken. In this study, Al5454-O alloy has been annealed and subjected to severe plastic deformation, where after corrosion, abrasion wear, and x-ray diffraction tests have been conducted. Data obtained has been evaluated accordingly.

2. TEST PROCEDURES

AA5454-O alloy has been used in our study. Chemical results were obtained by analysis that involved Al (96.4 %), Mg (2.95 %), Mn (0.265 %), Cr (0.045 %). Before proceeding with the test, AA5454-O alloy has been subjected to normalizing heat-treatment (annealing) with a view to eliminating grain size problems that might arise among the test samples. The alloy that was 10 mm in thickness has been cut into strips measuring 300 cm long and 100 mm wide. Rolling process has been fixed as 15 cycles/minute. Deformation rate is given in %.

Table 1. Wear test parameters

Parameters	Test conditions
Applied load, N	2
Velocity, mms^{-1}	197.9
Track diameter, mm	6
Environment/Medium	Air
Temperature, °C	19 ± 1
Relative humidity, RH %	40 ± 5
Time, s	600
Roughness *R*a, μm	0.12
WC-6%Co ball diameter, mm	5

Aluminium pieces have undergone rolling process at deformation rates of 10 – 20 – 30 – 40 – 50 – 60 – 70 – 80 % respectively. Since it was quite difficult to attain a high deformation rate in a single pass during the rolling process, rolling has not been applied in one pass. Instead, deformation rate has been increased by 10 % in each consecutive pass. Severely plastic deformed (SPD) aluminium blocks that were thus obtained have been prepared for wear and corrosion tests. Corrosion tests have been conducted in 3 % NaCl solution. Reference electrode was selected as Ag/AgCl sat whereas auxiliary, or in other words, counter electrode was chosen as Pt. Corrosion instrument used was VersaSTAT3 potentiometer. Abrasion wear tester has been selected as MarSurf XCR 20, V1.20-4. Wear test conditions are given in Table 1.

3. RESULTS

3.1. Constant current test analyses

Fig. 1 includes current density and time graphics, which indicate time-dependent exposure of samples to different current levels. Voltage has remained constant during the tests conducted. Fig. 1 has been used to investigate variation period of electrode current and pitting formation in the course of dipping time [19]. In all samples, current magnitude has risen during initial stages of dipping process. It has been observed that current density remained constant at around 180 s and thereafter. Graphics given in Figure 1 display constant current data by addition of a trend line and are plotted to indicate the change in current fluctuations. Highest current level has been determined as 20 mA. This change has started at 10 % and subsequently declined to the lowest level at 80 % deformation rate. Pitting corrosion has begun at around 180 s. It has been determined that current density got lower as the amount of plastic deformation got higher. The beginning time of pitting corrosion in test samples by forming bubbles under the same voltage effect with the voltage remaining constant and the change in pitting commencement resistance as dependent on deformation rate may be seen in Fig. 1 [19]. Current drawn by severely rolled samples was found to be lower than that of the samples which underwent plastic deformation at the least. It has been determined that there was an inverse relationship between the density of the current drawn and the corrosion resistance.

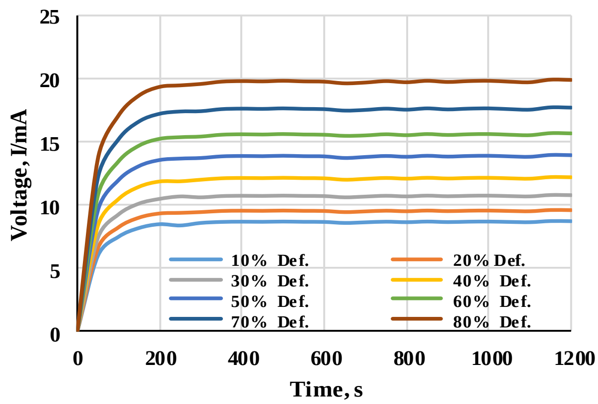

Fig. 1. Table of time-dependent current density at constant voltage (Trend line)

3.2. Potentiodynamic polarization

Evaluation respecting corrosion rate and corrosion characteristics has been made on the basis of potentiodynamic polarization test. Polarization curves for each sample are given in Fig. 2. Potentiodynamic values derived that have occurred based on deformation rate are shown in Fig. 2. It has been determined that corrosion was higher in the sample which underwent a deformation rate of 10 %. Corrosion potentiodynamic increased as the deformation rate got higher. Change in deformation rate has manifested a significant matter. While corrosion value has increased in an almost linear manner at 10 – 20 % and 30 – 60 % deformation rates, such corrosion value has exhibited a different trend in the case of 70 % and 80 % deformation rates, representing a decrease in corrosion resistance. Due to severe deformation of grains at the rate of 80% and increased grain boundaries associated with that process, corrosion occurring has changed from granular corrosion into intergranular corrosion [19]. At 1 % deformation rate, E_{corr} (anodic and cathodic corrosion potential) value has arisen as -1.4 and A_{corr} (log$I$ at Fig. 2) value as -4. On the other hand, same parameters were measured as -0.953 and -7.1 respectively at 80 % deformation rate. Data obtained has proven that the deformation rate was quite influential on corrosion of the aluminium alloy.

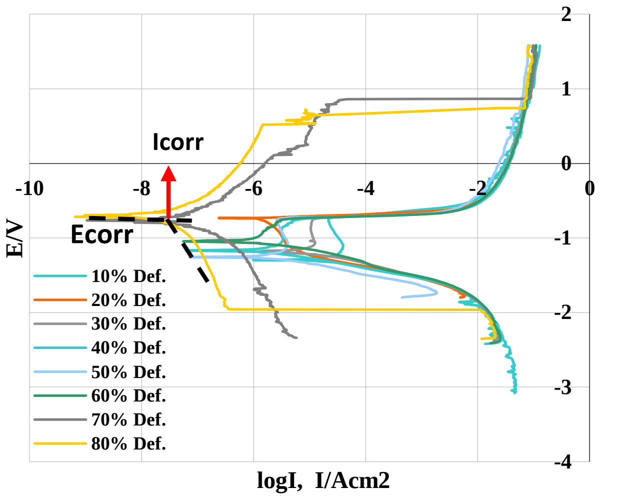

Fig. 2. Change in corrosion resistance by deformation rate

Fig. 3 indicates a plotted graph, which includes all corrosion values. According to this graph, it has been determined that corrosion rate changes in a parabolic low and proportional to deformation rate. In this graph, corrosion values arisen not only at 10 – 80 % deformation rates but also at those in between have been taken into consideration. Potentiodynamic values shown in Fig. 3 are quite significant and meaningful in terms of demonstrating how I (E_{corr}) and A (I_{corr}) values have changed. As A (I_{corr}) values got higher, I (E_{corr}) value has also increased in parallel to them. It may be said that the change occurring is parabolic, that A is denser between 5 and 13, and that it is inversely proportional to deformation rate.

The most distinguishing feature between Fig. 1 and Fig. 2 is as follows: in Fig. 1 we could identify at which time interval and at which current level began the corrosion, whereas in Fig. 2 we have obtained E_{corr} and I_{corr} values from Tafel curves. This is the most apparent difference in those two graphs that are similar to and correlated with each other.

3.3. Wear

In the graphics plotted as a result of abrasion wear test applied on AA5454-O alloy which was severely deformed by rolling process, change in friction coefficient (μ, Coulomb kinetic friction coefficients) and values of abrasion wear rate have been demonstrated. The change in friction coefficient on the basis of deformation rate is given in Fig. 4. As data involving friction coefficient is quite many in number, trendlines have been plotted at certain deformation rates. It has been observed that average values of friction coefficient of the deformed aluminium alloy decreased as the deformation rate got higher (Fig. 4). According to time-dependent change in values of friction coefficient, deformation rate has begun from 0.65 on the average and reached a maximum value of 0.67. In the case of 10 % deformation, abrasion wear rate was found as 0.0011 while friction value was determined as 0.67 max. On the other hand, in the case of 80 % deformation, such values were registered as 0.0002 and 0.648 respectively. As the rate of deformation got higher, abrasion wear resistance of Al alloy has increased but the friction coefficient has declined.

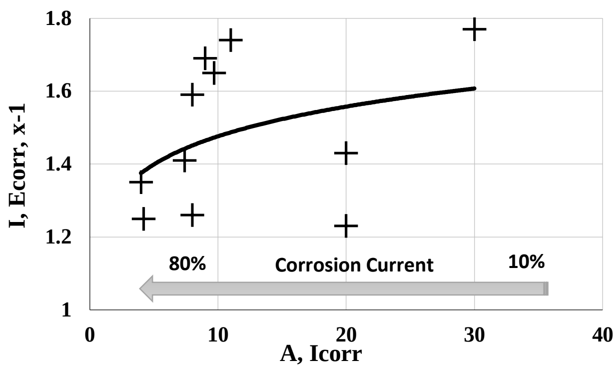

Fig. 3. Change in I_{corr}, E_{corr} values by deformation rate

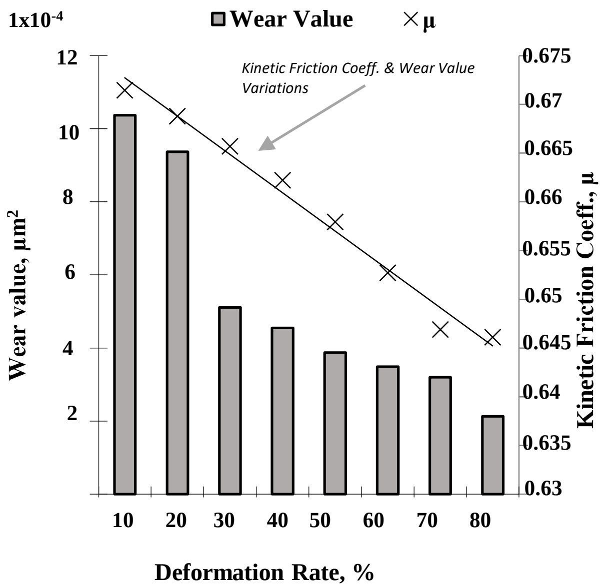

Fig. 4. Change in friction coefficient, μ – Coulomb friction coefficients, and wear lost value, according to different deformation rates

3.4. Hardness and XRD test results

The change occurring between roll pass and process history of aluminium 5454-O alloy is given in XRD figure cited [20]. Relative amount of $FeAl_3$ has decreased, relative amount of Mg_2Sn has increased, and relative amount of AlFeSi has shown no change up to 40 % deformation rate [20]. This situation indicates that, after the rolling process, hard and soft phases have resulted in reduced crystallite size [19]. As the diagram given in literature [20] depicts, the increase in % deformation rate has led to a decline in the peak value of Mg_2Sn [19]. Presence of the second phase arising at this point is of significance in terms of hardness of Al 5454-O. Based on these explanations, it may be said that corrosion has affected peak values of Mg_2Sn and AlFeSi at a considerable extent, and that a higher abrasion wear has occurred in those phases. As for hardness values, the hardness degree measured on the rolled surface is 78.2 HB on the average, representing a 10 % increase as compared to its untreated or unprocessed condition [20]. It has been observed that, since hardness degree of the material's surface gets higher as the rolling rate increases, abrasion wear value resulted in increased wear resistance of severely rolled Al alloy (Fig. 5).

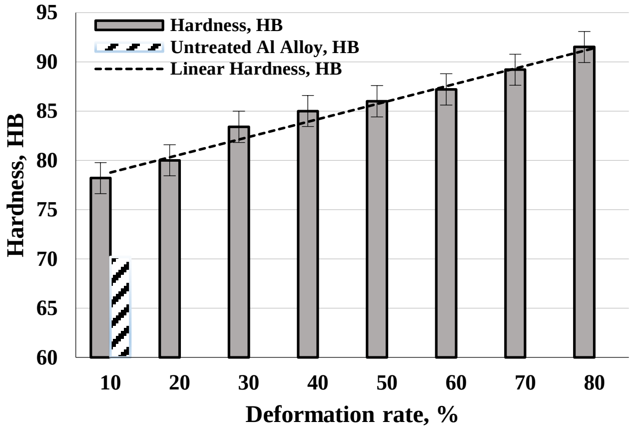

Fig. 5. The hardness changes with deformation rate, %, along contact rolling surfaces

4. DISCUSSION

In this study, severely deformed Al5454-O alloy has been subjected to corrosion, abrasion wear, hardness, and XRD analyses. Potentiodynamic analysis has shown that corrosion resistance is directly related to the intensity of current applied. Especially in respect of corrosion resistance, (voltage) current intensity must be approximately 180 I/mA so that pitting corrosion may begin and continue. Potentiodynamic analyses have indicated that the corrosion resistance of severely deformed Al alloy increased [1 – 3]. E_{corr} and A_{corr} values have got higher in parallel to the increase in deformation rate and corrosion resistance has been provided by means of severe plastic deformation [15 – 19]. As the deformation rate increased, corrosion resistance has shown a reverse development. Likewise, abrasion wear resistance of AA5454-O alloy has shown a change inversely proportional to deformation rate. Friction coefficient has exhibited a 10 % change resulting from the variation in deformation rate, representing a decline at severe deformation rates (70 – 80 %) [20]. Apart from the change in corrosion resistance, abrasion wear tests have changed hardness values registered on the rolled surface of severely deformed AA5454-O alloy, resulting in an increase in hardness degree in parallel to the deformation rate [4 – 20]. The rise in deformation rate has caused severe deformation of the alloy's grains thereby leading to manifestation of different mechanical properties within the alloy by individual elements of such alloy. Increase of surface hardness has changed friction coefficient of Al 5454-O alloy and has also given rise to an enhanced corrosion resistance. Hardness values of aluminium alloy that underwent deformation have increased as well, representing a change at the rate of 0.2 %.

In this study whereby abrasion wear and corrosion resistances of aluminium 5454-O alloy were investigated, corrosion value of severely deformed Al alloy has declined as the deformation rate got higher. This situation has manifested the presence of an inversely proportional relationship. On the other hand, abrasion wear resistance of the Al alloy that was severely deformed by rolling process has also changed depending on the variations in deformation rate.

5. CONCLUSIONS

The beginning time of corrosion has been determined by the help of the change in current density and the necessary preliminary data required to prevent electrochemical corrosion of Al5454-O has been recorded. Corrosion resistance of A15454-O has been identified by means of potentiodynamic polarization analysis and it has been observed that corrosion resistance increased by severe deformation. E_{corr} values of corrosion current have been determined. On the other hand, friction value (Coulomb friction coefficients) of Al5454-O has decreased by severe deformation. Likewise, abrasion wear rate has got lower by severe deformation due to the effect of friction. On the other hand, hardness values have significantly risen by severe deformation. XRD analyses have been used to observe the changes in FeA13, Mg2Sn and AlFeSi which are the main components or constituents of Al5454-O. In addition, preliminary data has been established for future TEM and SEM analyses.

REFERENCES

1. **Iwahashi, Y., Horita, Z., Nemoto, M., Langdon, T.G.** The Process of Grain Refinement in Equal-Channel Angular Pressing *Acta Materialia* 46 (9) 1998: pp. 3317 – 3331. https://doi.org/10.1016/S1359-6454(97)00494-1
2. **Valiev, R.Z., Langdon, T.G.** Principles of Equal-Channel Angular Pressing as a Processing Tool for Grain Refinement *Progress in Materials Science* 51 (7) 2006: pp. 881 – 981.
3. **Chung, C.S., Kim, J.K., Kim, H.K., Kim, W.J.** Improvement of High-Cycle Fatigue Life in a 6061 Al Alloy Produced By Equal Channel Angular Pressing *Materials Science and Engineering: A* 337 (1 – 2) 2002: pp. 39 – 44.
4. **Azimi, A., Shokuhfar, A., Nejadseyfi, O.** Mechanically Alloyed Al7075–Tic Nanocomposite: Powder Processing, Consolidation and Mechanical Strength *Materials & Design* 66 2015: pp. 137 – 141.
5. **Canakci, A.** Microstructure and abrasive wear behaviour of B4C particle reinforced 2014 Al matrix composites *Journal of Materials Science* 46 (8) 2011: pp. 2805 – 13. https://doi.org/10.1007/s10853-010-5156-2
6. **Canakci, A.**, **Varol, T., Erdemir, F., Ozkaya, S., Mindivan, H.** Microstructure and Properties of Fe-–Al Intermetallic Coatings on the Low Carbon Steel Synthesized

By Mechanical Alloying *The International Journal of Advanced Manufacturing Technology* 73 (5 – 8) 2014: pp. 849 – 858.

7. **Azimi, A., Fallahdoost, H., Nejadseyfi, O.** Microstructure, Mechanical and Tribological Behavior of Hot-Pressed Mechanically Alloyed Al–Zn–Mg–Cu Powders *Materials & Design* 75 2015: pp. 1 – 8.
8. **Meyer, L., Hockauf, M., Zillmann, B., Schneider, I.** Strength, Ductility and Impact Toughness of the Magnesium Alloy Az31b after Equal-Channel Angular Pressing *International Journal of Material Forming* 2 (1) 2009: pp. 61 – 64. https://doi.org/10.1007/s12289-009-0545-2
9. **Darmiani, E., Danaee, I., Golozar, M.A., Toroghinejad, M.R.** Corrosion Investigation of Al – SiC Nano-Composite Fabricated by Accumulative Roll Bonding (Arb) Process *Journal of Alloys and Compounds* 552 2013: pp. 31 – 39. https://doi.org/10.1016/j.jallcom.2012.10.069
10. **Nie, M., Wang, C., Qu, M., Gao, N., Wharton, J., Langdon, T.** The Corrosion Behaviour of Commercial Purity Titanium Processed by High-Pressure Torsion *Journal of Materials Science* 49 (7) 2014: pp. 2824 – 2831. https://doi.org/10.1007/s10853-013-7988-z
11. **Zheng, Z.J., Gao, Y., Gui, Y., Zhu, M.** Corrosion Behaviour of Nanocrystalline 304 Stainless Steel Prepared by Equal Channel Angular Pressing *Corrosion Science* 54 2012: pp. 60 – 67.
12. **Miyamoto, H., Harada, K., Mimaki, T., Vinogradov, A., Hashimoto, S.** Corrosion of Ultra-Fine Grained Copper Fabricated by Equal-Channel Angular Pressing *Corrosion Science* 50 (5) 2008: pp. 1215 – 1220. https://doi.org/10.1016/j.corsci.2008.01.024
13. **Jiang, J., Ma, A., Song, D., Yang, D., Shi, J., Wang, K., Chang, L., Chen, J.** Anticorrosion Behavior of Ultrafine-Grained Al-26 Wt% Si Alloy Fabricated By Ecap *Journal of Materials Science* 47 (22) 2012: pp. 7744 – 7750. https://doi.org/10.1007/s10853-012-6703-9
14. **Hoseini, M., Shahryari, A., Omanovic, S., Szpunar, J.A.** Comparative Effect of Grain Size and Texture on the Corrosion Behaviour of Commercially Pure Titanium Processed by Equal Channel Angular Pressing *Corrosion Science* 51 (12) 2009: pp. 3064 – 3067.
15. **Akiyama, E., Zhang, Z., Watanabe, Y., Tsuzaki, K.** Effects of Severe Plastic Deformation on the Corrosion Behavior of Aluminum Alloys *Journal of Solid State Electrochemistry* 13 (2) 2009: pp. 277 – 282.
16. **Shi, Y., Pan, Q., Li, M., Huang, X., Li, B.** Effect of SC And Zr Additions on Corrosion Behaviour of Al-Zn-Mg-Cu Alloys *Journal of Alloys and Compounds* 612 2014: pp. 42 – 50. https://doi.org/10.1016/j.jallcom.2014.05.128
17. **Shokuhfar, A., Nejadseyfi, O.** The Influence of Friction on the Processing of Ultrafine-Grained/Nanostructured Materials by Equal-Channel Angular Pressing *Journal of Materials Engineering and Performance* 23 (3) 2014: pp. 1038 – 1048.
18. **Vrátná, J., Hadzima, B., Bukovina, M., Janeček, M.** Room Temperature Corrosion Properties of Az31 Magnesium Alloy Processed by Extrusion and Equal Channel Angular Pressing *Journal of Materials Science* 48 (13) 2013: pp. 4510 – 4516. https://doi.org/10.1007/s11665-013-0849-8
19. **Nejadseyfi, O., Shokuhfar, A., Dabiri, A., Azimi, A.** Combining Equal-Channel Angular Pressing and Heat Treatment To Obtain Enhanced Corrosion Resistance in 6061 Aluminum Alloy *Journal of Alloys and Compounds* 648 2015: pp. 912 – 918. https://doi.org/10.1016/j.jallcom.2015.05.177
20. **Sezek, S., Aksakal, B.** Deformation and Temperature Behaviour During Cold, Warm and Hot Flat Rolling of Aa5454-O Alloy *Materials & Design* 30 (9) 2009: pp. 3450 – 3459.