Forming Limit Diagrams of Fine-Grained Al 5083 Produced by Equal Channel Angular Rolling Process

H.R. Rahimi, M. Sedighi, R. Hashemi*

School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

*Corresponding author:
e-mail: rhashemi@iust.ac.ir (R. Hashemi) Tel.: +98-21-77240540, Fax: +98-21-77240540

Abstract

The objective of this research is to study the strain forming limits of Al-Mg alloy (5083) sheet, fabricated by equal channel angular rolling process (ECAR) at room temperature. For this purpose, the ECAR process was executed at room temperature in three passes. Mechanical properties, micro-hardness, and microstructure were investigated after the ECAR process. Uniaxial tensile tests of the ECAR process produced samples and showed that yield and ultimate stresses increase, while the uniform elongation to fracture decreases in comparison with the annealed state. There was a continuous hardness enhancement by increasing the number of the ECAR passes. After the third pass, the amount of hardness raised by 73% in comparison with the annealed sample. In the fourth pass, the hardness reduced slightly, that was attributed to the strain saturation in room temperature and was followed by high surface cracks. In the annealed condition, the average grain size was 45µm, and after the third ECAR pass, this amount was reduced to 10µm. Furthermore, the forming limit diagrams (FLDs) were determined experimentally, using the Nakazima test. The obtained results show that after the third pass, the
FLDs’ level move downward, meaning that a reduction occurred in the forming limits of ECARRed samples.

Keywords: Equal channel angular rolling; Forming limit diagram; Sheet metals; Experiment

1. Introduction

In recent years, fabricating nanostructure sheet metals and alloys via severe plastic deformation (SPD) of metallic materials has been considered to a great extent, as it develops fine grains up to sub-micrometer or even nanometer order in polycrystalline materials [1, 2]. Ultrafine-grained (UFG) material has attracted significant research interest, because it reveals high strength besides good ductility and toughness. Recently, as one of the outstanding procedures to generate UFG sheet metallic materials, equal channel angular rolling (ECAR) has progressed [3-4]. ECAR is a type of SPD method by which large strains can be exerted to the material [5]. This method is based on equal channel angular pressing (ECAP) and has been lately used in few sheet and strip metals to produce UFG structure with favorable properties [6, 7]. ECAR can be considered as an affordable process in order to produce high-quality aluminum alloy sheets wherewith the material is passed across the channels of a die set, without variation in strip cross-section zone [8]. Therefore, it can be used in a continuous procedure and with various passes to produce ultrafine grains and favorable mechanical properties [7, 9]. The high-quality ECARRed alloy sheets can be utilized in automotive and airplane industries. When the metal sample passes through the intersection area of ECAR die channels, the shaping zone is found to be non-uniform. Therefore, the material undergoes simultaneous plastic deformations in different strain levels and locations [10].
In the literature, there is no investigation carried out on forming limit diagrams of ECARed sheets, especially for Al-Mg alloy (5083). Understanding the forming behavior of ECARed sheets plays an important role in its practical efficacy along with a thorough production cost analysis. The forming limit diagram (FLD) is widely accepted as an efficient tool to analyze the formability of sheet metals [11-24].

In this paper, the forming limit diagrams of fine-grained Al-Mg alloy (5083) sheets, fabricated by equal channel angular rolling process at room temperature were determined experimentally for the first time. For this purpose, the ECAR process was performed at room temperature in three passes. Mechanical properties, micro-hardness, and microstructure were investigated after the ECAR process. Finally, the FLDs were determined experimentally, using the Nakazima test.

2. Experimental Procedure

2.1. Material

In the present study, an aluminum alloy 5083 sheet with 2 mm thickness was cut in order to make specimens ready for the test. Then, the samples were annealed at 450 °C for one hour and were air-cooled according to American Society for Testing and Materials (ASTM) B918-01 to relieve all the internal residual stresses.

Non-heat-treatable aluminum-magnesium alloys (5XXX series) are used in different industries, e.g. marine, TV towers and cryogenics. They have primarily potential for lightweight structural application in automotive and aerospace industries. It is because of their properties such as corrosion resistance as well as reasonable strength, ductility and weld ability. It is believed that
recognition of forming capability in these alloys will enhance the potential for such applications [25].

The material chemical composition (in wt. %) was specified by quantometry analysis and is reported in Table 1. The quantometry analysis is a way by which we can measure the chemical composition of different elements in metal alloys. X-ray fluorescence (XRF) analysis is one of the most common non-destructive methods for qualitative as well as quantitative determination of elemental composition of materials. It is suitable for solids, liquids as well as powders. When high energy photons (x-rays or gamma-rays) are absorbed by atoms, inner shell electrons are ejected from the atom, becoming “photoelectrons”. This leaves the atom in an excited state, with a vacancy in the inner shell. Outer shell electrons then fall into the vacancy, emitting photons with energy equal to the energy difference between the two states. Since each element has a unique set of energy levels, each element emits a pattern of X-rays characteristic of the element, termed “characteristic X-rays”. The intensity of the X-rays increases with the concentration of the corresponding element [26].

**Table 1. Chemical composition (in wt. %) of Al 5083 Alloy**

| Element | Composition (wt. %) |
|---------|-------------------|
| Al      | Balance           |
| Mg      | 4.5               |
| Mn      | 0.7               |
| Fe      | 0.21              |
| Si      | 0.15              |
| Cr      | 0.15              |
| Cu      | 0.02              |
| Other   | 0.13              |

**2.2. Equal Channel Angular Rolling Process**

A schematic illustration of an ECAR set, utilized to introduce shear deformation into sheet metal samples is shown in Fig. 1a. The process was conducted with a rolling machine (two feeding
The outlet and inlet channels' thickness is 2 mm. In Fig. 1a, the curvature angle ($\psi$) is 0°, and the oblique angle ($\phi$) that is the intersection angle between the inlet and the outlet channels is 130°. The initial thickness of Al strip is 2 mm, is fed through the feeding rolls, and is reduced to 1.95 mm thickness strip. After passing through the forming zone, the sample preserves its primary thickness (2 mm).

Three overall paths are employed to pass the material through dies in the equal channel angular pressing (ECAP) process [27]. In path A, the specimen passes repeatedly without rotation. And in B and C paths, it is trundled by 90° and 180° after any passing, respectively. In the ECAR process, as opposed to ECAP process, there are only two overall feasible paths as material passage through dies, where A and C paths which are characterized in the ECAP process can be used for sheet metal samples. Fig. 2 is a schematic representation of A and C passing paths, feeding the rolls and dies assembled in ECAR equipment.

Fig. 1. (a) Schematic illustration of equal channel angular rolling process, (b) the upper die with fixtures
In this study, the ECAR process was done for three passes with 3 m/min feeding speed and processing path A. It is assumed that the bottom and top surfaces of the specimen are in contact with the lower and upper dies, respectively. Using Equation (1) [28], the effective shear strain inflicted to the sample after third pass will be 1.54:

$$\varepsilon_{\text{eff}} = \frac{2N}{\sqrt{3}} K^2 \cot \frac{\phi}{2}$$

(1)

In Equation (1), N represents the number of passes, $\phi$ is the angle of inclination, and K is the thickness ratio and is equal to 0.975. This equation is derived from the modified Segal model for shear deformation computation [28]. According to the experimental results, it can be considered that dimensional changes of length, thickness, and width of the sample are insignificant. The Al 5083 specimen, fabricated by the ECAR process at ambient temperature is shown in Fig. 3.
2.3. Experimental Setup for Sheet Metal Forming Limits Determination

The Nakazima deep drawing test is used to carry out the biaxial stretch-forming tests to obtain the FLDs [29, 30]. Rectangular samples of different widths were cut from the sheet metals with 200 mm length, perpendicular to the rolling direction. In order to mark the circular grid with 2.5 mm diameter on the surface of the sheet specimen, the electro-chemical method is used. For stretching sheet samples, a 50-ton constant speed hydraulic press was employed. An abrupt change in load–displacement diagram is utilized as the stopping criterion in the test (Fig. 4). The specimens with different geometries are used to obtain the forming limit curve in this research. Fig. 5 explains the geometries of the employed specimens in order to get the FLD [31]. The typical deformed samples can be observed in Fig. 6. The circular grids are deformed to elliptic shapes during the tests. After conducting the out-of-plane stretching test for each samples, the limited strains are determined from the major and minor axes of the ellipse that is located in the nearest distance from the localized necking zone. Therefore, Mylar tape is used (Fig. 7). Mylar tape is a graded transparent tape calibrated to the circular grid etched on the undeformed sheet. The tape is placed over an ellipse on the distorted sheet to match its major or minor diameter, enabling the strain to be read directly as a percentage [31]. The major and minor engineering
strains are calculated via Equations (2) and (3), respectively, and then are transformed into the true strain:

\[ \varepsilon_{\text{major}}(\%) = \frac{a-c}{c} \times 100 \]  

(2)

\[ \varepsilon_{\text{minor}}(\%) = \frac{b-c}{c} \times 100 \]  

(3)

Where a, b, and c denote the ellipse's the major and the minor diameters and the initial circle diameter, respectively.

Fig. 4. Showing a sudden drop force in load-displacement diagram obtained from the Nakazima test
Post-print of “HR Rahimi, M Sedighi, R Hashemi, (2018) Forming limit diagrams of fine-grained Al 5083 produced by equal channel angular rolling process, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 232(11), 922–930. https://doi.org/10.1177/1464420716655560

Fig. 5. The different specimen geometries to obtain the FLC (all the dimensions are in mm) [31]

Fig. 6. Typical deformed specimens
3. Results and Discussion

3.1. Tensile Behavior

An STM-50 (SANTAM Company) electronic tensile machine was employed to accomplish the tensile tests. The mechanical and material properties were determined by standard tests, using specimens which were prepared pursuant to ASTM-E8 characteristics at a constant crosshead speed of 2 mm/min [32]. The mechanical and material properties of each sample are presented in Table 2. Fig. 8 shows the stress-strain diagrams obtained from the uniaxial tensile tests for annealed and ECARed samples. It can be observed that by imposing severe plastic deformation on the specimen via equal channel angular rolling process, the yield and the ultimate strength increase, whereas the elongation to failure decreases. Based on the number of ECAR passes, changes in the ultimate strength, the yield strength, and the elongation at break, are demonstrated in Fig. 9. After the ECAR process, the yield strength (YS) and the ultimate tensile strength (UTS) are enhanced from 156 to 235 MPa and from 302 to 312 MPa, respectively, whereas the elongation at break is diminished from 16 to 11%. The substantial variations in mechanical attributes (yield and ultimate strength, and elongation at break) after the first pass can be ascribed to the strain hardening or dislocation reinforcement mechanisms, arising from the attendance of implicit dislocation boundaries of small disorientations [33, 34]. During the first pass of ECAR,
the large elongated grains are disrupted, and subsequently, the sub-grains with relative high
dislocation densities are formed, playing a crucial role in strengthening the metallic materials
after the first pass [35]. At this stage, the dislocation density in the inside and boundary of
primary coarse grains, increases, and a high fraction of low angle grain boundaries is formed [35,
36, and 37]. Although the enhancement in the strength persists until 3-pass, the rate of increase
was less than that of the first pass. The ECAR process leads to the substantial decrease in the
elongation at break, about 50%, until 3-pass. As shown in the stress-strain diagrams (Fig. 8), the
yield and the tensile strength had almost the same values in upper passes; however, by increasing
the number of ECAR passes the strain hardening was reduced.

Table 2. The material and the mechanical properties of Al5083 from the uniaxial tensile tests

| Sample     | Strain Hardening Exponent, n | Strength Coefficient, K, (MPa) | Yield Strength, (MPa) | Ultimate Tensile Strength, (MPa) | Elongation at Break, % |
|------------|------------------------------|-------------------------------|----------------------|-------------------------------|----------------------|
| Anneal     | 0.22                         | 535                           | 156                  | 302                           | 16                   |
| Pass 1 ECAR| 0.11                         | 434                           | 235                  | 312                           | 10                   |
| Pass 2 ECAR| 0.081                        | 462                           | 255                  | 324                           | 9                    |
| Pass 3 ECAR| 0.084                        | 457                           | 273                  | 345                           | 8                    |
3.2. Micro-Hardness

The micro-hardness values measured across the sheet thickness of ECARed samples are illustrated in Fig. 10. It is evident that after the first pass of the ECAR process, the micro-
hardness values increase significantly, and an approximate 37% increase is seen in comparison with the annealed samples. The rapid rise in micro-hardness in the first pass seems to be attributed to the strain hardening as a result of sub-grain boundary formations rather than grain refinements [38]. The subsequent ECAR passes do not lead to such considerable variations of micro-hardness. However, the rate of micro-hardness enhancement is saturated in next passes of ECAR. This phenomenon might also take place in other SPD processes (e.g., see [39, 40, and 41]). The strengthening in the next passes could be related to the rapid enhancement of dislocation density [39], followed by dislocations rearrangement to sub-grains (cells) and grain refinement [43-47]. The maximum amount of micro-hardness was obtained in the third pass, having increased by 73% in comparison with the annealed sample. Due to the large cracks on sheet surface after the fourth pass, the values declined slightly.

![Fig. 10. Changes in micro-hardness based on the number of ECARred passes](image-url)
3.3. Optical Micrographs

The optical micrographs of the annealed and 3-pass ECARed samples are shown in Fig. 11. The grain size of the samples was measured via the photo tool software. The average grain size of the annealed sample was about 45µm. It is heterogeneous and illustrates a typical recrystallized structure with angular grains (Fig. 13a). Grains of the third pass ECARed sample were reduced to ~10±5 µm (Fig. 13b).

3.4. Forming Limit Diagrams

As mentioned in Section 3 (Table 2), the mechanical properties and forming behaviors of different ECAR passes, obtained from tensile tests indicate that the yield strength of ECARed samples are somewhat higher than those of their base metals (annealed samples); besides, their strain hardening exponents are less than those of their base metals. In addition, the uniform elongations of ECARed samples are 62 to 100% less than those of their base metals. Fig. 12 shows the forming limit diagrams, obtained from experimental tests for the annealed samples and the first to third pass ECARed Al 5083. By comparing the achieved FLDs, it can be concluded
that the formability of ECARed samples will become less than that of related base metals through increasing the number of ECAR passes (Fig. 12). Moreover, it can be seen that after increasing the number of ECAR passes, the forming limit diagram slope increases on the left side and decreases on the right side. This phenomenon can be accounted for by the influences of the ECAR process on the microstructure and anisotropy of sheets.

![Fig. 12. The FLDs of annealed and first to third pass of ECARed aluminum 5083](image)

Table 3 shows the changes of micro-hardness, mechanical properties, and formability of aluminum (5083-O) ECARed in comparison with those of the annealed samples. The values in Table 3 were obtained, using Equation 4:

\[ \xi = \left( \frac{\alpha - \beta}{\beta} \right) \times 100 \]  

(4)

Where \( \alpha \) is defined as the value of the parameter in particular pass of the ECAR process, and \( \beta \) is the same parameter in the annealed sample.
Table 3. Percentage changes in the mechanical properties of annealed sample after the ECAR process

| Sample  | Micro-Hardness | Yield Strength | Ultimate Strength | Elongation at Break | FLD (%) |
|---------|----------------|----------------|--------------------|---------------------|---------|
| Annealed| 72 Hv          | 156 MPa        | 302 MPa            | 16 mm               | 0.21    |
| Pass 1  | 36.1 %         | 50.6 %         | 3.3 %              | -37.5 %             | -14.3%  |
| Pass 2  | 53.6 %         | 63.4 %         | 7.3 %              | -43.8 %             | -23.8%  |
| Pass 3  | 68.8 %         | 75 %           | 14.2 %             | -50 %               | -28.6%  |

4. Conclusions

In this research, the effects of the ECAR process on formability, mechanical properties, and the micro-structural evolution of Al (5083-O) were investigated at room temperature. The following results can be exposed:

(1). By means of the equal angle channel rolling process, an evident increase in the yield and ultimate strength may be achieved along with a decrease in elongation at break of samples, compared to the annealed samples. The yield strength value was 156 MPa in the annealed state which rose up to 273 MPa after the ECAR process third pass; and, in comparison with the annealed samples, a double increase in strength value was obtained. In addition, the effective strain, applied to the material after three passes of the ECAR process was 1.54. This effective strain quantity could be achieved in rolling process with about 75% reduction in thickness.

(2). The results showed that after the first pass of the ECAR process, the micro-hardness values increased significantly, and in comparison with the annealed sample, an approximate 37% increase was observed. This magnitude remained almost invariable during the process up to the third pass. Eventually, in the next passing due to created surface cracks, the micro-hardness was reduced slightly. The maximum available hardness after all the 3-passes of the ECAR process was 120 Vickers. That is a 73% increase, compared to the annealed condition.
The grain size of Al (5083-O) sheets was reduced by increasing the number of the ECAR passes. The maximum rate of grain refinement occurred during the first pass. The rate reduced in subsequent passes. The average grain size was 45 µm in the annealed condition, while after the third pass of the ECAR at room temperature, the average grain size was reduced to 10 µm.

(4). After three passes of the ECAR, the yield strength increased, whereas the elongation and formability decreased. However, the rates of the increase in yield strength and the decrease in the strain forming limits were not the same.

References

[1]. Valiev RZ, Krasilnikov NA, Tsenev NK. Plastic deformation of alloys with submicron-grained structure. Materials Science and Engineering: A. 1991; 137:35-40.

[2]. Xing ZP, Kang SB, Kim HW. Microstructural evolution and mechanical properties of the AA8011 alloy during the accumulative roll-bonding process. Metallurgical and Materials Transactions A. 2002; 33(5):1521-30.

[3]. Segal VM. Materials processing by simple shear. Materials Science and Engineering: A. 1995; 197(2):157-64.

[4]. Furukawa M, Iwahashi Y, Horita Z, Nemoto M, Langdon TG. The shearing characteristics associated with equal-channel angular pressing. Materials Science and Engineering: A. 1998; 257(2):328-32.

[5]. Iwahashi Y, Wang J, Horita Z, Nemoto M, Langdon TG. Principle of equal-channel angular pressing for the processing of ultra-fine grained materials. Scripta Materialia. 1996; 35(2):143-6.

[6]. Kim WJ, Yoo SJ, Chen ZH, Jeong HT. Grain size and texture control of Mg–3Al–1Zn alloy sheet using a combination of equal-channel angular rolling and high-speed-ratio differential speed-rolling processes. Scripta Materialia. 2009; 60(10):897-900.

[7]. Nam CY, Han JH, Chung YH, Shin MC. Effect of precipitates on microstructural evolution of 7050 Al alloy sheet during equal channel angular rolling. Materials Science and Engineering: A. 2003; 347(1):253-7.

[8]. Iwahashi Y, Horita Z, Nemoto M, Langdon TG. The process of grain refinement in equal-channel angular pressing. Acta Materialia. 1998; 46(9):3317-31.

[9]. Sedighi M, Mahmoodi M. Residual stresses evaluation in equal channel angular rolled Al 5083 by IHD technique: investigation of two calculation methods. Materials and Manufacturing Processes. 2012; 28(1):85-90.
Post-print of “HR Rahimi, M Sedighi, R Hashemi, (2018) Forming limit diagrams of fine-grained Al 5083 produced by equal channel angular rolling process, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 232(11), 922–930. https://doi.org/10.1177/1464420716655560

[10]. Keeler SP, Backofen WA. Plastic instability and fracture in sheets stretched over rigid punches. Asm Trans Q. 1963; 56(1):25-48.

[11]. Habibi M, Hashemi R, Ghazanfari A, Nghadabadi R, Assempour A. Forming limit diagrams by including the M–K model in finite element simulation considering the effect of bending. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 2016, 1464420716642258.

[12]. Hashemi R, Manus H, Masoumi A. A simulation-based approach to the determination of forming limit diagrams. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 2014, vol. 228 no. 12 1582-1591.

[13]. Zhang C, Leotoing L, Guines D, Ragneau E. Experimental and numerical study on effect of forming rate on AA5086 sheet formability. Materials Science and Engineering: A. 2010 Feb 15;527(4):967-72.

[14]. Zhang C, Chu X, Guines D, Leotoing L, Ding J, Zhao G. Dedicated linear–Voce model and its application in investigating temperature and strain rate effects on sheet formability of aluminum alloys. Materials and Design. 2015; 67:522-30.

[15]. Hashemi R, Abrinia K, Assempour A, Nejadkhaki HK, Mastanabad AS. Forming limit diagram of tubular hydroformed parts considering the through-thickness compressive normal stress. Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications. 2016; 230 (1): 332-343.

[16]. Martins PA, Bay N, Tekkaya AE, Atkins AG. Characterization of fracture loci in metal forming. International Journal of Mechanical Sciences. 2014; 83:112-23.

[17]. Wang K, Carsley JE, Zhang L, Stoughton TB, Li J, Carlson BE. Forming limits of an age hardenable aluminum sheet after pre-straining and annealing. International Journal of Mechanical Sciences. 2014; 82:13-24.

[18]. Babu NB, Davidson MJ, Rao AN, Balasubramanian K, Govindaraju M. Effect of differential heat treatment on the formability of aluminium tailor welded blanks. Materials and Design. 2014; 55:35-42.

[19]. Lee WB, Wen XY. A dislocation-based model of forming limit prediction in the biaxial stretching of sheet metals. International journal of mechanical sciences. 2006; 48(2):134-44.

[20]. Aghchaj AJ, Shakeri M, Dariani BM. Influences of material properties of components on formability of two-layer metallic sheets. The International Journal of Advanced Manufacturing Technology. 2013; 66(5-8):809-23.
Post-print of “HR Rahimi, M Sedighi, R Hashemi, (2018) Forming limit diagrams of fine-grained Al 5083 produced by equal channel angular rolling process, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 232(11), 922–930. https://doi.org/10.1177/1464420716655560

[21].  Assempour A, Hashemi R, Abrinia K, Ganjiani M, Masoumi E. A methodology for prediction of forming limit stress diagrams considering the strain path effect. Computational materials science. 2009; 45(2):195-204.

[22].  Nurcheshmeh M, Green DE. Investigation on the strain-path dependency of stress-based forming limit curves. International Journal of Material Forming. 2011; 4(1):25-37.

[23].  Hashemi R, Ghazanfari A, Abrinia K, Assempour A. Forming Limit Diagrams of Ground St14 Steel Sheets with Different Thicknesses. SAE International Journal of Materials & Manufacturing. 2012; 5(1):60-4.

[24].  Ito K, Satoh K, Goya M, Yoshida T. Prediction of limit strain in sheet metal-forming processes by 3D analysis of localized necking. International journal of mechanical sciences. 2000; 42(11):2233-48.

[25].  Zhalehfar F, Hashemi R, Hosseinipour SJ. Experimental and theoretical investigation of strain path change effect on forming limit diagram of AA5083. The International Journal of Advanced Manufacturing Technology. 2015; 76(5-8):1343-52.

[26].  R. Jenkin, X-ray Techniques: Overview in “Encyclopedia of Analytical Chemistry” R.A. Meyers (Ed.), Ó John Wiley & Sons Ltd, (2000) 13269–13288.

[27].  Naka T, Torikai G, Hino R, Yoshida F. The effects of temperature and forming speed on the forming limit diagram for type 5083 aluminum–magnesium alloy sheet. Journal of Materials Processing Technology. 2001; 113(1):648-53.

[28].  Lee JC, Seok HK, Han JH, Chung YH. Controlling the textures of the metal strips via the continuous confined strip shearing (C2S2) process. Materials Research Bulletin. 2001; 36(5):997-1004.

[29].  Kamachi M, Furukawa M, Horita Z, Langdon TG. Equal-channel angular pressing using plate samples. Materials Science and Engineering: A. 2003; 361(1):258-66.

[30].  Hashemi R, Faraji G, Abrinia K, Dizaji AF. Application of the hydroforming strain-and stress-limit diagrams to predict necking in metal bellows forming process. The International Journal of Advanced Manufacturing Technology. 2010; 46(5-8):551-61.

[31].  Ozturk F, Lee D. Experimental and numerical analysis of out-of-plane formability test. Journal of Materials Processing Technology. 2005; 170(1):247-53.

[32].  Metals Test Methods and Analytical Procedures, Annual Book of ASTM Standards, ASTM-E8 and ASTM-E517, West Conshohocken, PA 03.01 (2000).
Post-print of “HR Rahimi, M Sedighi, R Hashemi, (2018) Forming limit diagrams of fine-grained Al 5083 produced by equal channel angular rolling process, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 232(11), 922–930. https://doi.org/10.1177/1464420716655560

[33]. Habibi A, Ketabchi M. Enhanced properties of nano-grained pure copper by equal channel angular rolling and post-annealing. Materials & Design. 2012; 34:483-7.

[34]. Reihanian M, Ebrahimi R, Tsuji N, Moshksar MM. Analysis of the mechanical properties and deformation behavior of nanostructured commercially pure Al processed by equal channel angular pressing (ECAP). Materials Science and Engineering: A. 2008; 473(1):189-94.

[35]. Valiev RZ, Langdon TG. Principles of equal-channel angular pressing as a processing tool for grain refinement. Progress in Materials Science. 2006; 51(7):881-981.

[36]. Xue Q, Beyerlein IJ, Alexander DJ, Gray GT. Mechanisms for initial grain refinement in OFHC copper during equal channel angular pressing. Acta materialia. 2007; 55(2):655-68.

[37]. Kvačkaj T, Kováčová A, Kvačkaj M, Kočiško R, Lityńska-Dobrzyńska L, Stoyka V, Miháliková M. TEM studies of structure in OFHC copper processed by equal channel angular rolling. Micron. 2012; 43(6):720-4.

[38]. Faraji G, Mashhadi MM, Kim HS. Tubular channel angular pressing (TCAP) as a novel severe plastic deformation method for cylindrical tubes. Materials Letters. 2011; 65(19):3009-12.

[39]. Shaarbaa M, Toroghinejad MR. Nano-grained copper strip produced by accumulative roll bonding process. Materials Science and Engineering: A. 2008; 473(1):28-33.

[40]. Faraji G, Jafarzadeh H, Jeong HJ, Mashhadi MM, Kim HS. Numerical and experimental investigation of the deformation behavior during the accumulative back extrusion of an AZ91 magnesium alloy. Materials and Design. 2012; 35:251-8.

[41]. Janeček M, Čížek J, Dopita M, Král R, Srba O. Mechanical properties and microstructure development of ultrafine-grained Cu processed by ECAP. In Materials Science Forum 2008 (Vol. 584, pp. 440-445).

[42]. Faraji G, Mashhadi MM, Kim HS. Microstructural evolution of UFG magnesium alloy produced by accumulative back extrusion (ABE). Materials and Manufacturing Processes. 2012; 27(3):267-72.

[43]. Mahmoodi M, Sedighi M, Tanner DA. Investigation of through thickness residual stress distribution in equal channel angular rolled Al 5083 alloy by layer removal technique and X-ray diffraction. Materials and Design. 2012; 40:516-20.

[44]. Azimi A, Tutunchilar S, Faraji G, Givi MB. Mechanical properties and microstructural evolution during multi-pass ECAR of Al 1100–O alloy. Materials and Design. 2012; 42:388-94.
Post-print of “HR Rahimi, M Sedighi, R Hashemi, (2018) Forming limit diagrams of fine-grained Al 5083 produced by equal channel angular rolling process, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 232(11), 922–930. https://doi.org/10.1177/1464420716655560

[45]. Mahmoodi M, Sedighi M, Tanner DA. Experimental study of process parameters’ effect on surface residual stress magnitudes in equal channel angular rolled aluminium alloys. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 2014:0954405414522449.

[46]. Habibi A, Ketabchi M, Eskandarzadeh M. Nano-grained pure copper with high-strength and high-conductivity produced by equal channel angular rolling process. Journal of Materials processing technology. 2011; 211(6):1085-90.

[47]. Chen ZH, Cheng YQ, Xia WJ. Effect of equal-channel angular rolling pass on microstructure and properties of magnesium alloy sheets. Materials and Manufacturing Processes. 2007; 22(1):51-6.

Appendix I: Notation

| Abbreviation | Definition                                      |
|--------------|------------------------------------------------|
| SPD          | Severe Plastic Deformation                     |
| UFG          | Ultra-Fine Grain                               |
| O            | Anneal                                         |
| ECAP         | Equal Channel Angular Pressing                 |
| ECAR         | Equal Channel Angular Rolling                  |
| FLD          | Forming Limit Diagram                          |
| FLDₚ₀        | Major strain in plane strain state             |
| ε₁           | Major strain                                   |
| ε₂           | Minor strain                                   |
| ψ            | Curvature angle                                |
| φ             | Oblique Angel                                  |
| YS           | Yield Strength                                 |
| UTS          | Ultimate Strength                              |
| n            | Strain hardening index                         |
| K            | Strength coefficient                           |