UNIVERSITI PUTRA MALAYSIA

MECHANICAL PROPERTIES OF ULTRA-FINE GRAIN ALUMINIUM AL6063 AND PURE COPPER PROCESSED BY EQUAL CHANNEL ANGULAR EXTRUSION METHOD

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By

JAMSHID NEMATI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

July 2015

DEDICATIONS

Dedicated to my family and in particular to my wife, *Tayebeh* whose love, support, and encouragement are the most wonderful of the many blessings that God has granted me.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for Degree of Doctor of Philosophy

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Faculty : Engineering

Severe plastic deformation (SPD) is one of the processes used to refine the microstructure of materials among which the Equal Channel Angular Extrusion (ECAE) is the most common method. ECAE has gained much interest over the past decades. In this study, pure copper and aluminum alloy 6063 grain refinement were performed using the ECAE method. The materials were extruded up to eight and six passes at room and 200°C temperatures with a constant ram speed of 20 and 30 mm/min, respectively, following route A through a die angle of 90° between the die channels. Optical microscopic examinations revealed pure copper grain refinements in the range of 32 µm to 4 µm after eight passes whereas for Al-6063 alloy the grain diameter reduced from 45 µm to 2.8 µm after six passes of ECAE. The extruded specimens were tested under quasi-static, medium and high strain rate loadings using various testing machines. Mechanical properties of the extruded material were obtained at different strain rates. For the pure copper, it was found that the maximum increased of ultimate strength of 80% occurred after the second pass for the V=200 mm/min. The total increase of ultimate strength after eight passes was around 100%. Furthermore, hardness, increased to a maximum of 36% after eight passes.

The results of Al-6063 tensile tests indicated that the tensile yield stress (YS) and ultimate tensile strength (UTS) of the extruded specimens increased significantly after 5 passes of ECAE process. The average increase was found to be around 70%, regardless of the tension velocities. The hardness measurements were made on different locations of the billet. For Al-6063, the results indicated around 90% increase in microhardness after 5 passes. The results for pure copper illustrated that the most increase of hardness (about 18%) occurs after the 2nd pass. A total of around 36% increase in hardness was observed after 8 passes.

A maximum increase in impact energy absorption of 100% was achieved from Charpy tests after eight passes and 90% after six passes of the ECAE process for pure copper and Al-6063 alloy, respectively. In addition, bending fatigue test results indicates that for fatigue tested pure copper specimens, the results of fatigue tests indicated that a significant improvement in fatigue life occurred after the 2nd pass. For low stresses, a maximum increase in fatigue resistance of approximately 500% was observed. The results of fatigue tested Al-6063 specimens indicate that major improvements in fatigue resistance occurred after the first pass. The impact strength of extruded specimens was also evaluated for different passes at a strain rate of 1800 s^{-1} using Split-Hopkinson pressure bar (SPHB). The results indicated that the major strength improvement for Al-6063 and pure copper in the 5^{th} and 6^{th} passes and 6^{th} and 8^{th}occurred, respectively. Finally, ECAE process was simulated using the DEFORM-3D software through a three-dimensional analysis.

Abstrakt tesis yang dikemukakan kepada Senat Universiti Pura Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

SIFAT MEKANIKAL BUTIRAN HALUS ALUMINIUM AL6063 DAN TEMBAGA TULEN YANG DIPROSES DENGAN KAEDAH SEMPERITAN SALURAN SAMA PENYEMPERITAN SUDUT (ECAE)

Oleh

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Mengubah bentuk plastik teruk adalah satu proses yang digunakan untuk mengecilkan struktur mikro bahan dimana antara cara yang digunakan ialah Saluran Sama Penyemperitan Sudut (ECAE). ECAE telah diminati beberapa dekad lalu. Dalam kajian ini, tembaga tulen dan aloi Aluminium 6063 penghalusan bijian/struktur telah dilakukan menggunakan kaedah ECAE. Bahan-bahan ini telah disemperitkan sehingga lapan dan enam laluan pada suhu bilik dan 200°C dengan halaju ram yang tetap 20 dan 30 mm/min, melalui sudut acuan 90° antara saluran-saluran acuan. Pemeriksaan mikroskop optik mendapati penghalusan bijian tembaga tulen adalah antara 32µm hingga 4µm selepas melalui lapan laluan tetapi untuk aloi Al-6063 garispusat bijian berkurang dari 45µm ke 2.8 µm selepas enam laluan ECAE. Sifat-sifat mekanikal hasil ECAE telah dikaji. Spesimen semperitan telah diuji dibawah kuasi-statik, bebanan kadar terikan pertengahan dan tinggi menggunakan berbagai mesin ujian. Sifat-sifat mekanikal bahan tersemperit diperolehi pada kadar terikan berbeza. Untuk tembaga tulen, didapati kekuatan muktamad maksima 80% bertambah berlaku pada laluan kedua dengan kelajuan V=200 mm/min. Jumlah kenaikan kekuatan muktamad selepas laluan kelapan adalah 100%. Tambahan pula, kekerasan bertambah sehingga maksima 36% selepas lapan laluan. Specimen secara fractografi menunjukkan bahawa mekanisma keretakan adalah tidak bergantung kepda kadar terikan.

Keputusan ujian tegangan Al-6063 menunjukkan tegasan alah tegangan (YS) dan kekuatan tegangan muktamad (UTS) spesimen disemperit bertambah dengan ketara selepas 5 laluan proses ECAE. Purata kenaikan sekitar 70% telah diperolehi tanpa mengira kelajuan tegangan. Ini menunjukkan sifat tegangan specimen tidak dipengaruhi oleh kadar terikan.Pengukuran kekerasan telah dibuat pada kedudukan berbeza bilet. Untuk Al-6063, keputusan menunjukkan penambahan 90% kekerasan mikro selepas 5 laluan. Keputusan untuk tembaga tulen menyatakan kekerasan banyak bertambah (18%) berlaku selepas laluan kedua. Jumlah sebanyak 36% pertambahan kekerasan dilihat selepas 8 laluan. Penambahan maksima penyerapan tenaga hentaman 100% dicapai melalui ujian Charpy selepas lapan laluan dan 90% selepas enam laluan proses ECAE untuk tembaga tulen dan Al-6063.

Sebagai tambahan, specimen lesu bentuk-tulang-anjing telah dihasilkan dari spesimen semperitan dengan laluan dan tanpa laluan. Untuk ujian kelesuan specimen tembaga tulen, keputusan kelesuan menunjukkan penambahbaikan ketara kehidupan keletihan berlaku selepas laluan ke 2. Untuk tegasan rendah, didapati tahan keletihan bertambah maksima hampir 500%. Keputusan ujian kelesuan spesimen AL-6063 menunjukan penambahbaikkan major dalam tahan kelesuan berlaku selepas laluan pertama. Kekuatan hentaman specimen semperitan juga dinilai pada laluan berbeza dengan kadar terikan 1800 s^{-1} menggunakan Split-Hopkinson Pressure Bar (SPHB). Keputusan menunjukkan penambahbaikan kekuatan major untuk Al-6063 dan tembaga tulen dalam laluan ke 5 dan ke 6, dan laluan ke 6 dan ke 8. Akhirnya, proses ECAE telah disimulasikan menggunakan perisian DEFORM-3D melalui analisis tiga-dimensi.

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I certify that a Thesis Examination Committee has met on 13 July 2015 to conduct the final examination of Jamshid Nemati on his thesis entitled "Mechanical Properties of Ultra-Fine Grain Aluminium AL6063 and Pure Copper Processed by Equal Channel Angular Extrusion Method" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

ARB	Accumulative Roll Bonding
ASTM	American Society for Testing and Materials
CEC	Cyclic Extrusion-Compression
CVD	Chemical Vapor Deposition
d	Average grain diameter
ECAE	Equal Channel Angular Extrusion
EDM	Electro Discharge Machining
FEM	Finite Element Method
HCF	High-Cycle Fatigue
HPT	High Pressure Torsion
IGC	Inert Gas Condensation
K_y	Material constants
LCF	Low-Cycle Fatigue
MF	Multiaxial Forging
NC	Noncrystalline Materials
OM	Optical Microscope
PEEQ	Equivalent Plastic Strain
RCS	Repeated Corrugation and Straightening
SEM	Scanning Electron Microscope
SHPB	Split-Hopkinson Pressure Bar
SPD	Severe Plastic Deformation
UFG	Ultrafine Grained Materials
UTS	Ultimate Tensile Strength
VH	Vickers Hardness
YS	Yield Strength
ó6	Strain rate
µ	Friction Coefficient
1_o	Material constants
$ů_y$	Yield stress
ū	Die channel angle
ɣ	The angle of the arc of curvature of die

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

In materials engineering, it is essentially important to characterize and improve the mechanical properties, among which the strength, ductility, fatigue life, and others. The fact is that microstructure, which affects the material mechanical performance, also determines the mechanical properties of any materials directly. Hence, the materialôs average grain size, particularly plays a very substantial and dominating role. In this context, those materials which have grain sizes ranging from 100 to 1000 nm, i.e. <1-εm, are called Ultra-Fine Grain (UFG) materials (Srinivasan, et al., 2006), which even have grain sizes bigger than the nano-materials and are seemingly recognized as the materials having grain sizes less than 100 nm. While there have been voluminous attentions given to the bulk UFG materials throughout the last two decades, several techniques have also been simultaneously devised aimed at manufacturing UFG materials. For instance, in order to transform and refine the materialsô microstructure, the Severe Plastic Deformation (SPD) process is exploited, which is in detail describes as a kind of deformation being able to deform a billet of material beyond a true strain of 4.00. In addition, in order to refine the microstructural grain, numerous kinds of SPD are commonly utilized. Illustrations of such kinds are drawing, rolling, swaging, 3- axes deformation, and equal channel angular extrusion (Heffner, 2008).

A lot of of endeavors have been so far borne directed on manufacturing the bulk ultra-fine/nanostructured materials directly from micro structured ones by making use of the SPD. Particularly with the equal channel angular extrusion/processing (ECAE/ECAP) which is referred to as the most economical method and the easiest one to execute among the other SPD methods. It is admitted that one reason for such properties is the simplicity in both processing and tooling (Abd El Aal, 2011). The first instance of its development was reported in the former Soviet Union in the early 1990s by V.M. Segal (Segal, 1995). Since then, the materials community has tremendously focused on the ECAE process on account of its capability to yield ultrafine- grained metals as well as offering novel properties (Chen, et al., 2003).

It is accentuated that the ECAE process was principally concomitant with structure refinement to sub-micron scale (Segal, 2004). Refining the grain size leads to the dislocation pile-up at the grain boundary which accordingly hampers the dislocation movement as well as boosting the materialôs yield stress. It is repeatedly proved that this technique can be used for significantly enhancing the materialsô mechanical properties in consort with their microscopic structures.

A review was undertaken to examine using the ECAP for grain refinement by altering the conventional ECAP with the purpose of boosting the process efficiency and the techniques used for up-scaling the procedure as well as processing the materials which were hard-to-deform (Valiev and Langdon, 2006). Figure 1.1 schematically exhibits the ECAE process wherein the specimens with square or circular cross section are strained by consecutive extrusion processes.

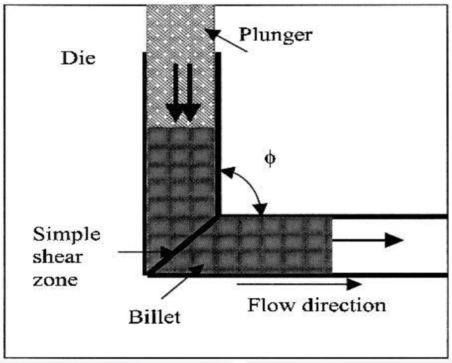

Figure 1-1:Schematic process of ECAE
(Salem, H. G., & Lyons, J. S. 2002)

The ECAE technique revolves around refining the metals and alloys microstructure which ultimately results in the material strengthening. According to the Hall-Petch relationship (Etch, 1953), this technique is mathematically described as follows:

$$ů_y = ů_o + \frac{K_y}{\sqrt{d}} \qquad (1.1)$$

where $ů_y$ is the yield stress, $ů_o$ and K_y are the materialsô constants, while d is the average grain diameter. The ECAE is particularly distinctive due to the fact that the cross sectional area of the workpiece will be unaffected in the course severe deformation; nonetheless, extrusion and drawing the area decreases in other processes such as forging. It should be noted that the material in the ECAE technique is extruded through a channel and around a corner which have mostly an angle of 90°. Once the work piece passes by this corner, it experiences fairly large strains, at times, of the order of 1.5. Furthermore, the strains at the consecutive passes amass causing more material refinement as the section of the workpiece will be equal on the entrance and exit of the die.

It should be pinpointed that better enhancement will be given into the billet mechanical behavior so long as the number of passes increases (up to 7 to 8 times of extrusions). The ECAE is advantageous as the billet is capable of supporting severe deformations as well as sustaining large strains larger than one while it never struggle with the change in the dimensions. The core fact is that the materials grain turns out to be finer owing to these large strains. It should be noticed that the grain refinement is carried on after each extrusion pass. This process can eventually yield a nano-structures material (Patil Basavaraj, et al., 2008) while such a process is not burdened with the weaknesses typically associated the other producing techniques like the milling and compaction. In details, the latter mentioned techniques are concomitant with few issues, including impurities, cavities, buckling and fracturing.

Over the last two decades, a great deal of research has been conducted to comprehensively investigate the microstructural aspects of the materials which have been generated through the ECAE. The microstructure of a copper was scrutinized by Huang et al. (2004) which had been developed by means of the ECAE to a strain ý 8 employing two different strain paths by way of rotating the billets through 90°or180° between each pass. Moreover, the nano-structured copperôs (NC) properties were significantly affected by the heat treatment and the hardening cyclic deformation in the viscoplastic regime (Kommel et al., 2007). Also, the mechanical properties related to a 6063-T1 aluminum alloy have been studied while this alloy was processed via the ECAP method up to nine passes, revealing that the SPD (ECAP processing) could significantly enhance the Al 6063 alloysô mechanical properties through grain refinement (Serban et al., 2012). Furthermore, it is found that at the room temperature, the annealing temperature can remarkably influence the microhardness of the as-processed material (Daly, et al., 2009).

Moreover, under constant stress testing, a significant enhancement of fatigue limit and fatigue life has been reported in the ultrafine-grained state revealing that numerous cyclic properties related to the severely-predeformed materials having fine grains can be reorganized with regard to the HallïPetch grain boundary hardening as well as dislocation hardening (Vinogradov, et al., 2001). Likewise, the tensile properties and impact toughness of Znï40Al alloy subjected to the ECAE have been examined demonstrating that elongation to fracture noticeably upsurges corresponding to the rise in the number of ECAE passes as well as proving that there is an escalation in the strength after the first pass while there will be a decrease for the succeeding passes. Such softening is claimed to occur by reason of the deformation-induced homogenization alongside the incessant change in the composition of the constituting phases with the number of passes. Another related conclusion is that as a result of the significant growth in ductility, multi-pass ECAE could be employed to improve the impact toughness of the alloy (Pureck et al., 2004).

1.2. Statement of the Problem

As stated earlier, scientists and engineers have been fascinated in ultrafine grains (UFG) and nanostructured (NC) materials for more than two decades. In recent times, many advances have also been obtained in processing and characterizing these two materials due to their boosted properties, namely their high tensile strength, high toughness, excellent fatigue life, as well as their likelihood to get superplasticity at the low temperatures (Kim et al., 2003; Tham et al.,2007). Along with an ever-increasing demand on the improved materials performance, there is an urge for ultra-fine grain-sized materials which yield greater strength while there is no deterioration in the materialsô ductility. Of numerous existing severe plastic deformations, the ECAE technique has proved capable in developing the ultra-fine grained microstructures in bulk samples. It is also substantiated by Segal that the simple shear (SS) taking place on the die intersection plane can be used to estimate the deformation in the ECAE under ideal conditions (Beyerlein et al., 2008).

To date, it is discerned that the majority of the published literature investigating the effect of the ECAE process has only examined few mechanical properties and/or microstructure of the materials under study, leaving out a dearth of much more comprehensive studies. Moreover, there are still some unanswered questions on the impact this process imposes on the materialsô mechanical properties. What follows is a brief account of such questions:

1. Is there any limitation in grain refinement in a metal or alloy using the ECAE method?
2. Does the improvement of mechanical properties of the material keep rising with grain refinement? Or does it have a critical point?
3. To what extent can the improvement of materialsô mechanical properties be achieved using the ECAE method?
4. Are the responses if the ECAEed materials in quasi static, dynamic, and cyclic loads similar to the normal materials?
5. What is the fracture mechanism regime of the ECAEed materials under different loading conditions?

To address the above mentioned questions, this study was conducted to investigate the mechanical properties and microstructure as well as their relationship of pure copper and aluminum alloy 6063 processed using the multi-pass ECAE method.

1.3. Research Objectives

The main objective established in this research study was to refine and homogenize the microstructure of commercially pure copper and aluminum alloy 6063 via the Severe Plastic Deformation (SPD) employing the Equal Channel Angular Extrusion (ECAE). Moreover, the effects of grain refinement on mechanical properties improvement of the processed materials using ECAE were examined. To fulfill the main objective, the following specific objectives were addressed:
1. To predict the force and speed of the plunger during the ECAE process.
2. To determine the strength, structure and fracture toughness of extruded pure copper and Al-6063 alloy after different ECAE passes.
3. To determine the fatigue life of the extruded materials.

1.4. Scope and Limitations of the Study

The focus of this research is to study the mechanical properties improvements while it deals with grain refinement of the materials by SPD is employing the ECAE method and explores its effects on microstructure and mechanical properties. In details, the study focused on AL-6063 alloy and pure copper as they both entailed satisfactory workability as well as possessing extensive applications in industry. The research was conducted through the two subsequent stages while only one of the materials was examined in each stage:

¶ During the first stage, the pure copper was employed and the received material was annealed and extruded through the ECAE method for a maximum of eight passes. The point is that this process was carried out at the room temperature in a die made up of two channels of equal cross-section intersecting at an angle 90°, having corner angle of 20°. Afterwards, by using 2, 4, 6 and 8 passes, the ECAE tests were executed while eight specimens were tested during each pass. In order to prepare the specimens for mechanical characterization and microstructural examination of the extruded materials, the tested billets were employed.

¶ During the second stage, identical processes were executed for the annealed Al-6063 alloy. In details, the ECAE tests were achieved by employing 1, 2, 3, 4 and 5 passes following route A at the temperature which varied from 195°C to 205°C. Eight specimens were tested during each pass. The tested billets were used to prepare the specimens for mechanical characterization and microstructural examination of the extruded materials.

It should be asserted that this research study encountered two main limitations. In the first place, by increasing the number of ECAE passes, the extrusion force will increase, necessitating a pressing machine with higher capacity as well as requiring a die and plunger with high strength and such demands were almost impossible. In the second place, the extruded specimens became shorter after each pass of the ECAE process; this was the case because after a definite amount of the ECAE passes, their suitable length became too short as to prepare the samples for most of the examination tests on the mechanical properties; these tests included the tensile, fatigue, fracture toughness, and so on.

1.5. Organization of the Thesis

This thesis is organized in ten chapters. Chapter one presents a general introduction consisting; Background of the Study, problem statement, research objective and scope and Limitations of the Study. In chapter two a review of literature that relates to the ECAE process and its effect on the mechanical properties of processed materials as well as their microstructure is presented. Description of methods used in the study and investigated materials provided in chapter three.

Chapter four discusses finite element and metallurgical study of properties of deformed pure copper by ECAE at various strain rates. An investigation of microhardness characteristics of Al-6063 alloy processed by Equal Channel Angular Extrusion is presented in chapter five. Chapter six discusses the improvements in the microstructure and fatigue behavior of pure copper using equal channel angular extrusion (ECAE).

Chapter seven discusses the experimental study of impact strength of Al-6063 alloy processed by Equal Channel Angular Extrusion. Chapter eight is related to the results and discussion of the development of microstructure and fracture toughness of AL-6063 alloy using equal channel angular extrusion. Chapter nine discusses the effect of equal channel angular extrusion on Al-6063 bending fatigue characteristics.

Chapter ten discusses the outcomes of the research; provides answers to the research questions and also how the objectives of the research were fulfilled. The chapter ends with conclusions and setting a direction for future research which could further investigate some aspects of this research.

BIBLIOGRAPHY

A. Vigradov, & Hashimoto, S. (2001). Multiscale phenomena in fatigue of ultra-fine grain materials- an overview. Materials Transactions, 42(1), 74-84.

Abd El Aal, M. I. (2011). Influence of the pre-homogenization treatment on the microstructure evolution and the mechanical properties of AlïCu alloys processed by ECAP.*Materials Science and Engineering A 528*, 6946-6957.

Aljobouri, A. A., & Sharif, N. M. (2010). Influence of die angles on the microhardness of aluminum alloy processed by equal channel angular pressing. *IIUM Engineering Journal,11 (2)*, 137-149.

Aour, B., Zaёri, F., Naёt-Abdelaziz, M., Gloaguen, J. M., Rahmani, O., & Lefebvre, J. M. (2008). A computational study of die geometry and processing conditions effects on equal channel angular extrusion of a polymer. *International Journal of Mechanical Sciences, 50*, 589-602.

Assadi , H., Gartner, F., Stoltnhoff, T., & Kreye, H. (2003). Bonding mechanism in cold gas spraying.*Acta Materialia, 53*, 4379-4394.

Azushima, A., Kopp, R., Korhonen, A., Yang, D. Y., Micari, F., Lahoti, G. D., et al. (2008). Severe plastic deformation (SPD) processes for metals. *CIRP Annals - Manufacturing Technology, 57*, 716ï735.

Balasundar, I., & Raghu, T. (2010).Effect of friction model in numerical analysis of equal channel angular pressing process.*Materials and Design, 31*, 449-457.

Beausir, B. t., Biswas, S., Kim, D. I., To´th, L. s. S., & Suwas, S. (2009). Analysis of microstructure and texture evolution in pure magnesium during symmetric and asymmetric rolling.*Acta Materialia, 57*, 5061ï5077.

Beyerlein, I. J., Field, R. D., Hartwig, K. T., & Necker, C. T. (2008).Texture development in two-pass ECAE-processed beryllium. In J. Mater (Ed.), *Ultrafine-Grained Materials* (pp. 7465ï7473): Springer.

Beyerlein, I. J., & Tóth, L. S. (2009).Texture evolution in equal-channel angular extrusion. Progress in Materials Science, 54, 427-510.

Bondar, M. P., & Merzhievskii, L. A. (2006). Evaluation of the microstructure and conditions of local strain localization under high-strain-rate loading, *Combusion, explosion and shock waves, 42*, 356-365.

Cardoso, K. R., Travessa, D. N., Botta, W. J., &Jr.A.M., J. (2011). High Strength AA7050 Al alloy processed by ECAP: Microstructure and mechanical properties. *Materials Science and Engineering A, 528*, 5804-5811.

Cerri, E., Marco, P. P. D., & Leo, P. (2009). FEM and metallurgical analysis of modified 6082 aluminum alloys processed by multipass ECAP: Influence of material properties and differentprocess settings on induced plastic strain.*journal of materials processing technology 209*, 1550-1564.

Chen, Y. C., Huang, Y. Y., Chang, C. P., & Kao, P. W. (2003). The effect of extrusion temperature on the development of deformation microstructures in 5052 aluminum alloy processed by equal channel angular extrusion.*Acta Materialia, 51*, 2005-2015.

Chen, Y. J., Chai, Y. C., Roven, H. J., Gireesh, S. S., Yu, Y. D., & Hjelen, J. (2012). Microstructure and mechanical properties of AlïxMg alloys processed by room temperature ECAP.*materials Science and Engineering A*, *545*, 139ï 147.

Chinta Babu, U., Prasad, K., & Kamat, S. V. (2011).Effect of strain rate on tensile behaviour of cryo-rolled ultrafine grained OFHC copper.*Transactions of The Indian Institute of Metals*, *64*(3).

Cojocaru, V.-D., ķerban, N., Raducanu, D., Cinca, I., & ķaban, R. (2010). Microstructural observations of fracture surfaces forIA 6063-T1 ECAP processed aluminum alloy *U.P.B. Sci. Bull.*, *72*(4), 163-173

Cole, B. N., & Sturges, J. L. (2003). The flying wedge: a method for high-strain-rate tensile testing. Part 2.Characteristics of the device.*International journal of impact engineering*, *28*, 891ï908.

Dadbakhshi, S., Karimi Taheria, A., & Smith, C. W. (2010). Strengthening study on 6082 Al alloy after combination of aging treatment and ECAP process. *Materials Science and Engineering A*, *527*, 4758ï4766.

Dalla Torre F., Lapovok R., & Sandlin J. (2004).Microstructures and properties of copper processed by equal channel angular extrusion for 1ï16 passes.Acta Mater 52, 4819ï4832.

Dalla Torre, F., Spatig, P., Schaublin, R., & Victoria, M. (2005).Deformation behaviour and microstructure of nanocrystalline electrodeposited and high pressure torsioned nickel.*Acta Materialia, 53*, 2337ï2349.

Dalla Torre, F. H., Ha ̈nzi, A. C., & Uggowitzer, P. J. (2008). Microstructure and mechanical properties of microalloyed and equal channel angular extruded Mg alloys. *Scripta Materialia*, *59*, 207ï210.

Daly, R., Khitouni, M., & Nabil, N. (2008).Microstructural and mechanical properties of copper processed by Equal Channel Angular ExtrusionI. In I. A. Lukôyanchuk & D. Mezzane (Eds.), *Smart Materials for Energy*: Springer Science + Business Media.

Daly, R., Zghal, S., & Njeh, N. (2009).Effects of annealing on the microstructure and properties of Cua1copper processed by Equal Channel Angular Extrusion.*Physics Procedia, 2*, 677-684.

Deng, G. Y., Lu.C., Su, L. H., Liu, X. H., & Tieu, A. K. (2012). Modelling texture evolution during ECAP of copper single crystal by crystal plasticity FEM. *Materials Science and Engineering A*, *534*, 68-74.

Ding, S. X., Lee, W. T., Chang, C. P., Chang, L. W., & Kao, P. W. (2008). Improvement of strength of magnesium alloy processed by equal channel angular extrusion.*Scripta Materialia*, *59*, 1006ï1009.

Ding, S. X., Chang, C. P., & Kao, P. W. (2009). Effects of Processing Parameters on the Grain Refinement of Magnesium Alloy by Equal-Channel Angular Extrusion.*Metallurgical and Materials Transactions A, 40A*, 415-425.

Ehab A., E. -D. (2012). Mechanical properties, microstructure and micro-texture evolution for 1050AA deformed by equal channel angular pressing (ECAP) and post ECAP plane strain compression using two loading schemes.*Materials and Design*, *34*, 793ï807.

Estrin, Y., & Vinogradov, A. (2010). Fatigue behaviour of light alloys with ultrafine grain structure produced by severe plastic deformation: An overview. *International Journal of Fatigue, 32*, 898ï907.

Etter, A. L., Baudin, T., Rey, C., & Penelle, R. (2006).Microstructural and textural characterization of copper processed by ECAE.*Materials Characterization*, 19-25.

Fang, D. R., Zhang, Z. F., Wu, S. D., Huang, C. X., Zhang, H., Zhao, N. Q., et al. (2006). Effect of equal channel angular pressing on tensile properties and fracture modes of casting AlïCu alloys.*Materials Science and Engineering A, 426*, 305-313.

Filho, A. d. A. M., Prados, E. F., Valio, G. T., Rubert, J. B., Sordi, V. L., & Ferrante, S., Maurizio. (2011). Severe Plastic Deformation by Equal Channel Angular Pressing: Product Quality and Operational Details. *Materials Research., 14* (3), 335-339.

Foley, D. C., Hartwig, K. T., Maloy, S. A., Hosemann, P., & Zhang, X. (2009). Grain refinement of T91 alloy by equal channel angular pressing.*Journal of Nuclear Materials*, *389*, 221-224.

Foley, D. C., Al-Maharbi, M., Hartwig, K. T., Karaman, I., Kecskes, L. J., & Mathaudhu, S. N. (2011). Grain refinement vs. crystallographic texture: Mechanical anisotropy in a magnesium alloy. Scripta Materialia, 64, 193-196.

Fu, M. W., Tham, Y. W., Hng, H. H., & Lim, K. B. (2009). The grain refinement of Al-6061 via ECAE processing: Deformation behavior,microstructure and property. *Materials Science and Engineering A, 526*, 84ï92.

Gabor, P., Maier, H. J., & Karaman, I. (2006). Effect of strain rate on fatigue behavior of ultrafine grained copper. *Fracture of Nano and Engineering Materials and Structures*, 209-210.

Gabor, P., Canadinc, D., Maier, H. J., Hellmig, R. J., & Zuberova, Z. (2007).The Influence of Zirconium on the Low-Cycle Fatigue Response of Ultrafine-Grained Copper.*Metallurgical and Materials Transaction A, 38,* 1916-1926.

Gao, L., & Cheng, x. (2008). Microstructure and mechanical properties of Cuï10%Alï 4%Fe alloy produced by equal channel angular extrusion.*Materials and Design, 29*, 904-908.

Greger, M., Kocich, R., Ļ²ģek, L., & Kander, L. (2006).Ultrafine grain formation during equal channel angular extrusion in an Al-Mg-Si alloy.*Journal of Achievements in Materials, 15* (1-2), 181-185.

Hall, E. O. (1951). *Deformation Processes in Nanostructured Metals and Alloys.* Paper presented at the Physical Society.

Han S., Lim C., & Kim C. (2005).The microstructural evolution during the equal channel angular pressing process and its relationship with the tensile behavior of oxygen-free copper. Metallurg Mater Trans A, 36, 467ï470.

Hans Raj, K., Setia, R., Sharma, R. S., Sahai, A., & Sharma, S. (2011). *Artificial Neural Network Modelling of Equal Channel Angular Pressing (ECAP) for Agile Manufacturing*. Paper presented at the International Conference on Agile Manufacturing Systems 2011.

Haouaoui, M., Karaman, I., Maier, H. J., & Hartwig, K. T. (2004).Microstructure Evolution and Mechanical Behavior of Bulk Copper Obtained by Consolidation of Micro- and Nanopowders Using Equal-Channel Angular Extrusion.*Metallurgical and Materials Transactions A, 35A*, 2935-2949.

Hazra, S. S., Pereloma, E. V., & Gazder, A. A. (2011). Microstructure and mechanical properties after annealing of equal-channel angular pressed interstitial-free steel. *Acta Materialia, 59*, 4015ï4029.

Heffner, W. (2008).*Microstrucrure development in 6000 series aluminum alloys processed via equal channel angular extrusion.*Florida state university, Florida.

Hockauf, M., Meyer., L. W., Halle., T., Kuprin., C., Hietschold., M., Schulze., S., et al. (2006). Mechanical properties and microstructural changes of ultrafine-grained AA6063T6 during high-cycle fatigue.*Int. J. of Mate Research, 97*, 1392-1400.

Hockauf, M., Meyer, L. W., & Krüger, L. (2008).Combining equal-channel angular extrusion (ECAE) and heat treatment for achieving high strength and moderate ductility in an Al-Cu alloy.*Materials Science Forum, 584*, 685-690.

Hoseini, M., Meratian, M., Toroghinejad, M. R., & Szpunar, J. A. (2010).The role of grain orientation in microstructure evolution of pure aluminum processed by equal channel angular pressing. M aterials Characterization 61, 1371-1378.

Houston, K. M. (2007). *Effects of strain path on the microstructure of aluminium alloys during Equal Channel Angular Pressing (ECAP).*Naval Postgraduate School, Monterey, CA 93943-5000.

Hu, H.-j., Zhang, D.-f., & Pan, F.-s. (2010). Die structure optimization of equal channel angular extrusion for AZ31 magnesium alloy based on finite element method. *Trans.Nonferrous.Sos.China*, *20*, 259-266.

Huang, W. H., Wu, C. Y., Kao, P. W., & Chang, C. P. (2004). The effect of strain path and temperature on the microstructure developed in copper processed by ECAE. *Materials Science and Engineering A, 366*, 221-228.

Huang, C. X., Wang, K., Wu, S. D., Zhang, Z. F., Li, G. Y., & Li, S. X. (2006). Deformation twinning in polycrystalline copper at room temperature and low strain rate.*Acta Materialia*, *54*, 655ї665.

Huang, C. X., Yang, G., Gao, Y. L., Wu, S. D., & Zhang, Z. F. (2008). Influence of processing temperature on the microstructures and tensile properties of 304L stainless steel by ECAP. *Materials Science and Engineering A*, *485*, 643ї650.

Islamgaliev, R. K., Kulyasova, O. B., Migler, B., Zehethauer, M., & Minkow, A. (2008). Structure and Fatigue Properties of the Mg Alloy AM60 Processed By ECAP. *Materials Science Forum, 584*, 803-808.

Iwahashi, Y., Wang, J., Horita, Z., Nemoto, M., & Langdon, T. G. (1996).Principle of equal-channel angular pressing for the processing of ultra-fine grained materials, *Scripta Materialia, 35*, 143ї146.

Jiang, J.-f., Lin, X., Wang, Y., Qu, J., & Luo, S.-j.(2012). Microstructural evolution of AZ61 magnesium alloy predeformed by ECAE during semisolid isothermal treatment.*Trains.Nonferrous.Sos. China*, *22*, 555-563.

Jin, Y. G., Baek, H. M., Hwang, S. K., Im, Y.-T., & Jeon, B. C. (2012). Continuous high strength aluminum bolt manufacturing by the spring-loaded ECAP system. *Journal of Materials Processing Technology, 212*, 848-855.

Jufu, J., Ying, W., Zhiming, D., Jianjun, Q., Yi, S., & Shoujing, L. (2010).Enhancing room temperature mechanical properties of Mgї9AlїZn alloy by multi-pass equal channel angular extrusion.*Journal of Materials Processing Technology, 210*, 751-758.

Kang, D.-H., & Kim, T.-W.(2010). Mechanical behavior and microstructural evolution of commercially pure titanium in enhanced multi-pass equal channel angular pressing and cold extrusion.*Materials and Design*, *31*, S54їS60.

Khan, A. S., & Meredith, C. S. (2010).Thermo-mechanical response of Al 6061 with and without equal channel angular pressing (ECAP).*International Journal of Plasticity*, *26*, 189-203.

Khodabakhshi, F., Kazeminezhad, M., & Kokabi, A. H. (2010).Constrained groove pressing of low carbon steel: Nano-structure and mechanical properties.*Materials Science and Engineering A, 527*, 4043-4049.

Kim, I., Kim, J., Shin, D. H., Lee, C. C., & Hwang, S. K. (2003).Effects of equal channel angular pressing temperature on deformation structures of pure Ti.*Materials Science and Engineering A, 342*, 302-310.

Kim, D. I., Yang, D. Y., & Yoon, J. W. (2008).Investigation of microstructure characteristics of commercially pure aluminum during equal channel angular extrusion.*Materials Science and Engineering A, 485*, 621ï626.

Kim, D. I., Yang, D. Y., & Yoon, J. W. (2010). Microstructural evolution and its effect on mechanical properties of commercially pure aluminum deformed by ECAE (Equal Channel Angular Extrusion) via routes A and C. *Materials Science and Engineering A, 527*, 7927ï7930.

Kim, H. S., Kim, W. Y., & Song, K. H. (2012). Effect of post-heat-treatment in ECAP processed Cuï40%Zn brass. *Journal of Alloys and Compounds, 36*, 200-203.

Kim J.S., & Huh H. (2011). Evaluation of the material properties of an OFHC copper film at high strain rates using a micro-testing machine. Exp Mech 51, 845ï855.

Koch, c. C. (Ed.).(1953). Nanostructured Materials Processing, Properties and Potential Applications (Vol. 1). New York, U.S.A: William Andrew Publishing Norwich.

Kommel, L., Hussainova, I., & Volobueva, O. (2007).Microstructure and properties development of copper during severe plastic deformation.*Materials and Design, 28*, 2121ï2128.

Kubota, M., Wu, X., Xu, W., & Xia, K. (2010). Mechanical properties of bulk aluminium consolidated from mechanically milled particles by back pressure equal channel angular pressing. *Materials Science and Engineering A, 527*, 6533ï6536.

Kucukomeroglu, T. (2010). Effect of equal-channel angular extrusion on mechanical and wear properties of eutectic Alï12Si alloy. *Materials and Design, 31*, 782ï789.

Lapovok.R., Loader, C., Dalla Torre, F. H., & Semiatin, S. L. (2006). Microstructur evolution and fatigue behavior of 2124 aluminum processed by ECAE with back pressure.*Materials Science and Engineering A, 425*, 36-46.

Lapovok, R., To´th, L. s. S., Molinari, A., & Estrin, Y. (2009). Strain localisation patterns under equal-channel angular pressing. *Journal of the Mechanics andPhysics of Solids, 57*, 122-136.

Li, W. Y., Liao, H., Li, C., Li, G., Coddet, C., & Wang, X. (2006).On high velocity impact of micro-sized metallic particles in cold spraying.Application surface science, 253, 2852-2862.

Liwei, L., Tianmo, L., Yong, C., Liguang, W., & Zhongchang, W. (2012). Double change channel angular pressing of magnesium alloys AZ31. *Materials and Design, 35*, 138-143.

Luk§ġ p., Kunz L., & M., S. (2008). Fatigue of ultrafine- grained copper. Paper presented at the Proceedings of the 6th International Conference on Low Cycle Fatigue (LCF6), Berlin.

Luri, R., LuisPérez, C. J., Salcedo, D., Puertas, I., Pérez, I., & Fuertes, J. P. (2011).Evolution ofdamage in AA-5083 processed by equal channel angular extrusion using different die geometries.*Journal of Materials Processing Technology, 211* (1), 48-56.

Macheret, J., Korth, G. E., Herling, D. R., Smith, M. T., Lillo, T. M., & Watkins, A. D. (1999).*Equal Channel Angular Extrusion*. Idaho Falls, Idaho 83415: Idaho National Engineering and Environmental Laboratoryo.

Majzoobi G.H. (1990). Experimental and numerical studies of metal deformation and fracture at high strain rates. PhD Thesis, University of Leeds, UK, 1990.

Majzoobi, G. H., Barton, D. C., & Ramezani, M. (2007). Stress wave effects in the Flying Wedge high strain rate tensile testing device. *journal of strain, 42*, 1-11.

Meyer, L. W., Hockauf, M., Zillmann, B., & Schneider, I. (2009). Strength, ductility and impact toughness of the magnesium alloy AZ31B after equal-channel angular pressing. *Int J Mater Form, 2*, 61-64.

Mishin, O. V., Bowen, J. R., & Lathabai, S. (2010). Quantification of microstructure refinement in aluminium deformed by equal channel angular extrusion: Route A vs. route Bc in a 90^0 die. *Scripta Materialia, 63*, 20-23.

Mishra, A., Richard, V., Gr´egori, F., Asaro, R. J., & Meyers, M. A. (2005).Microstructural evolution in copper processed by severe plastic deformation.*Materials Science and Engineering A, 410-411*, 290ï298.

Mishra, A., Kad, B. K., Gregori, F., & Meyers, M. A. (2007). Microstructural evolution in copper subjected to severe plastic deformation: Experiments and analysis. *Acta Materialia, 55*, 13-28.

Mishra, A., Martin, M., Thadhani, N. N., Kad, B. K., Kenik, E. A., & Meyers, M. A. (2008). High-strain-rate response of ultra-fine-grained copper.*Acta Materialia*.

Mogucheva, A., & Kaibyshev, R. (2010). Fatigue properties of a 1421 aluminum alloy processed by ECAE. *J. of Phys. Conf. Ser., 240*, 1-5.

Mughrabi, H., & Höppel, H. W. (2010).Cyclic deformation and fatigue properties of very fine-grained metals and alloys.*International Journal of Fatigue, 32*, 1413-1427.

Mughrabi H., Höppel H.W., Kautz M., & Valiev R.Z. (2003). Annealing treatments to enhance thermal and mechanical stability of ultrafine-grained metals produced by severe plastic deformation Z. Metallkd, 94(10), 1079-1086.

Niendorf, T., Canadinc, D., Maier, H. J., Karaman, I., & Yapici, G. G. (2007).Microstructureïmechanical property relationships in ultrafine-grained NbZr. *Acta Materialia, 55*, 6596ï6605.

Niendorf, T., Canadinc, D., Maier, H. J., & Karaman, I. (2007).On the Microstructural Stability of Ultrafine-Grained Interstitial-Free Steel under Cyclic Loading.*Metallurgical and Materials Transactions A,38A*, 1946-1955.

Niendorf, T., Maier, H. J., Canadinc, D., Yapici, G. G., & Karaman, I. (2008).Improvement of the fatigue performance of an ultrafine-grained NbïZr alloy by nano-sized precipitates formed by internal oxidation.*Scripta Materialia, 58*, 571-574.

Niendorf, T., Maier, H. J., Canadinc, D., & Karaman, I. (2009).Cyclic stability of ultrafine-grained interstitial-free steel at elevated temperatures.*materials Science and Engineering A, 503*, 160-163.

Niendorf, T., Dadda, J., Canadinc, D., Maier, H. J., & Karaman, I. (2009).Monitoring the fatigue-induced damage evolution in ultrafine-grained interstitial-free steel utilizing digital image correlation.*Materials Science and Engineering A, 517*, 225-234.

Olejnik, L., & Rosochowski, A. (2005).Methods of fabricating metals for nano-technology.*Bull.Pol.AC., 53*(4), 413-423.

Patil Basavaraj, V., Chakkingal, U., & Prasanna Kumar, T. S. (2008). *Influence of friction in Equal Channel Angular Pressing - A study with simulation*. Paper presented at the Metal 2008.

Patil Basavaraj, V., Chakkingal, U., & Prasanna Kumar, T. S. (2009).Study of channel angle influence on material flow and strain inhomogeneity in equal channel angular pressing using 3D finite element simulation.*journal of materials processing technology, 209*, 89-95.

Perig, A. V., Laptev, A. M., Golodenko, N. N., & Erfort, Y. A. (2010). Equal channel angular extrusion of soft solids.*Materials Science and Engineering A, 527*, 3769-3776.

Purcek, G., Altan, B. S., Miskioglu, I., & Ooi, P. H. (2004). Processing of eutectic Znï5% Al alloy by equal-channel angular pressing. *Journal of Materials Processing Technology, 148*, 279ï287.

Purcek, G. (2005). Improvement of mechanical properties for ZnïAl alloys using equal-channel angular pressing. *Journal of Materials Processing Technology, 169*, 242-248.

Purcek, G., Saray, O., Karaman, I., & Kucukomeroglu, T. (2008).Effect of severe plastic deformation on tensile properties and impact toughness of two-phase Znï40Al alloy.*materials Science and Engineering A, 490*, 403ï410.

Purcek, G., Saray, O., Kul, O., Karaman, I., Yapici, G. G., Haouaoui, M., et al. (2009). Mechanical and wear properties of ultrafine-grained pure Ti produced by multi-pass equal-channel angular extrusion. *Materials Science and Engineering A, 517* (97-104).

Purcek, G., Saray, O., & Kul, O. (2010).Microstructural Evolution and Mechanical Properties of Severely Deformed Al-12Si Casting Alloy by Equal-Channel Angular Extrusion.*Met.Mater. Int., 16* (1), 145-154.

Qiu J., Murata T., Wu T., Kitagawa M., & Kudo M. (2012).Plastic deformation mechanism of crystalline polymer materials in the equal channel angular extrusion process.Journal of Materials Processing Technology, 212, 1528ï 1536.

Rebhi, A., Makhlouf, T., Njah, N., Champion, Y., & Couzinié, Eap. (2009). Characterization of aluminum processed by equal channel angular extrusion: Effect of processing route.*Materials characterization, 60*, 1489-1495.

Saiyi Li. (2009). Comments on óóTexture evolution by shear on two planes during ECAP of a high-strength aluminum alloyò. Scripta Materialia 60, 356ï358.

Salem, H. G., & Lyons, J. S. (2002).Effect of Equal Channel Angular Extrusion on the Microstructure and Superplasticity of an Al-Li Alloy.*Journal of Materials Engineering and Performance, 11* (4), 384-391.

Saravanan, M., Pillari, R. M., Pai, B. C., Brahmakumar, M., & Ravi, K. R. (2006).Equal channel angular pressing of pure aluminium ð an analysis.*Bull. Mater. Sci., 29*(7), 679-684.

Segal, V. M. (1995). Materials processing by simple shear.*Materials Science and Engineering A, 197*, 157ï164.

Segal, V. M. (1999). Equal channel angular extrusion: from macromechanics to structure formation. *Materials Science and Engineering A, 271*, 322-333.

Segal, V. M. (2004). Engineering and commercialization of equal channel angular extrusion (ECAE) *Materials Science and Engineering A, 386*, 269-276.

Segal, V. M. (2005). Deformation mode and plastic flow in ultra fine grained metals. *Materials Science and Engineering A 406*(1-2), 205-216.

Segal, V. M. (2006). Tensile testing of ultra fine grained metals. *Materials Science and Engineering A, 422*, 321ï326.

Segal, V. M. (2008). Equal channel angular extrusion of flat products.*Materials Science and Engineering A, 476*, 178ï185.

Serban, N., Cojocaru,V.-D., & Butu, M. (2012). Mechanical Behavior and Microstructural Development of 6063-T1 Aluminum Alloy Processed by Equal-Channel Angular Pressing (ECAP): Pass Number Influence. *JOM, 64* (5), 607-614.

Seungzeon, H., Chayong, L., Changjoo, K., & Sangshik, K. (2005).The microstructural evolution during the equal channel angular pressing process and its relationship with the tensile behavior of oxygen-free copper.*Metallurg.Mater. Trans A, 36*, 467-470.

Shih, M. H., Yu, C. Y., Kao, P. W., & Chang, C. P. (2001). Microstructure and flow stress of copper deformed to large plastic strains. *Scripta Materialia, 45*, 793-799.

Skrotzki, W., Scheerbaum, N., Oertel, C.-G., Arruffat-Massion, R., & Suwas, S. (2007). Microstructure and texture gradient in copper deformed by equal channel pressing. *Acta Materialia, 55*, 2013-2024.

Srinivasan, R., Chaudhury, P. K., Cherukuri, B., Han, Q., & Swenson, D. (2006).*Continuous Severe Plastic Deformation Processing of Aluminum Alloys*: Wright State Universityo. Document Number)

Stobrawa, J. P., & Rdzawski, Z. M. (2009).Characterisation of nanostructured copper - WC materials.*Journal of Achievements in Materials and Manufacturing Engineering, 32* (2), 171-178.

Sun, P. L., Cerreta, E. K., Gray III, G. T., & BingertI, J. F. (2006).The Effect of Grain Size, Strain Rate, and Temperature on the Mechanical Behavior of Commercial Purity Aluminum.*Metallurgical and Materials Transactions A, 37A*, 2983-2994.

Sun, H. Q., Shi, Y.-N., Zhang, M.-X., & Lu, K. (2007). Plastic strain-induced grain refinement in the nanometer scale in a Mg alloy. *Acta Materialia, 55*.

Suo, T., Yulong, L., Qiong, D., & Yuanyong, L. (2007).Optimal pressing route for continued equal channel angular pressing by finite element analysis.*materials Science and Engineering A, 466*, 166-171.

Suwas, S., Arruffat-MASSION, R., TÓth, L. S., Fundenberger, J.-J., Eberhardt, A., & Skrotzki, W. (2007). Evolution of Crystallographic Texture during Equal Channel Angular Extrusion of Copper: The Role of Material Variables. *Metallurgical and Materials Transactions A*, 739-753.

Suwas, S., Bhowmik, A., & Biswas, S. (2009). Ultra-fine Grain Materials by Severe Plastic Deformation: Application to Steels. In A. Haldar, S. Suwas & D. Bhattacharjee (Eds.), *Microstructure and Texture in Steels* (pp. 325-344): Springer.

Talebanpour, B., Ebrahimi, R., & Janghorban, K. (2009). Microstructural and mechanical properties of commercially pure aluminum subjected to Dual Equal Channel Lateral Extrusion. *Materials Science and Engineering A, 527*, 141-145.

Tang, W. N., Chen, R. S., Zhou, J., & Han, E. H. (2009). Effects of ECAE temperature and billet orientation on the microstructure, texture evolution and mechanical properties of a MgïZnïYïZr alloy. *Materials Science and Engineering A, 499*, 404-410.

Tham, Y. W., Fu, M. W., Hng, H. H., Yong, M. S., & Lim, K. B. (2007). Study of deformation homogeneity in the multi-pass equal channel angular extrusion process.*Journal of Materials Processing Technology, 192-193*, 121-127.

Tolaminejad, B., & Dehghani, K. (2012).Microstructural characterization and mechanical properties of nanostructured AA1070 aluminum after equal channel angular extrusion.*Materials and Design, 34*, 285-292.

Tyrone L. Jones, & Kondoh, K. (2011).*Ballistic Analysis of New Military Grade Magnesium Alloys for Armor Applications*. APG,MD,21005-5066,USA: US army research laboratory.

Uday, C., & Thomson, P. F. (2001).Development of microstructure and texture during high temperature equal channel angular extrusion of aluminium.*Journal of Materials Processing Technology, 117*, 169-177.

Valiev, R. Z., & Langdon, T. G. (2006).Principles of equal-channel angular pressing as a processing tool for grain refinement.*Progress in Materials Science, 51*, 881-981.

Vinogradov, A. Y., Stolyarov, V. V., Hashimoto, S., & Valiev, R. Z. (2001). Cyclic behavior of ultrafine-grain titanium produced by severe plastic deformation.*Materials Science and Engineering A, 318*, 163ï173.

Vinogradov, A., & Hashimoto, S. (2001). Multiscale Phenomena in Fatigue of Ultra-Fine Grain Materials - an Overview.*Materials Transactions, 42*(1), 74-84.

Warmuzek.M. (2004). Aluminum-Silicon Casting Alloys: An Atlas of Microfractographs. *ASM International.*, 39-44.

Wei, Q., Jiao, T., Mathaudhu, S. N., Ma, E., Hartwig, K. T., & Ramesh, K. T. (2003).Microstructure and mechanical properties of tantalum after equal channel angular extrusion (ECAE).*Materials Science and Engineering A, 358*, 266-272.

Wong, M. K., Kao, P. W., Lui, J. T., Chng.C.P.,& Kao, P. W. (2007). Cyclic deformation of ultrafine-grained aluminum.*Acta Materialia, 55*, 715-725.

Xia, K., & Wu, X. (2005).Back pressure equal channel angular consolidation of pure Al particles.*Scripta Materialia 53,* 1225-1229.

Xi-Shu, W., LI, J., Ying, L., & Xing-Wu, G. (2008).Effect of equal channel angular extrusion process on deformation behaviors of Mg-3Al-Zn alloy.*Materials Letters, 62*, 1856ï1858.

Yang, F., & Okazaki, K. (2007). Indentation behavior of aluminum processed by equal channel angular extrusion: Effect of bending angle. *Scripta Materialia, 56*, 185-188.

Yang, X.-y., Sun, Z.-y., Jie, X., Miura, H., & Sakai, T. (2008). Grain size and texture changes of magnesium alloy AZ31 during multi-directional forging. Trans.Nonferrous.Sos.China, 18, s200-s204.

Yi-Lang, Y., & Shyong, L. (2003). Finite element analysis of strain conditions after equal channel angular extrusion. *Journal of Materials Processing Technology, 140*, 583ï587.

Yoon, S. C., Quang, P., Hong, S. I., & Kim, H. S. (2007). Die design for homogeneous plastic deformation during equal channel angular pressing. *Journal of Materials Processing Technology, 187-188*, 46-50.

Zeng, R., Enhou, H., Wei, K., Dietze, W., Kainer, K. U., & Atrens, A. (2010). Influence of microstructure on tensile properties and fatigue crack growth in extruded magnesium alloy AM60. *International Journal of Fatigue, 32*, 411-419.

Zhang, J., Zhang, K.-s., Wu, H.-C., & Yu, M.-h.(2009). Experimental and numerical investigation on pure aluminum by ECAP.*Trans.Nonferrous.Sos.China, 19*, 1303-1311.

Zhang, D.-f., Hu, H.-j., Pan, F.-s., Yang, M.-b., & Zhang, J.-p.(2010). Numerical and physical simulation of new SPD method combining extrusion and equal channel angular pressing for AZ31 Magnesium alloy.*Trans.Nonferrous.Sos.China*, *20*, 478-483.

Zhu, Y. T., & Lowe, T. C. (2000).Observations and issues on mechanisms of grain refinement during ECAP process.*Materials Science and Engineering A, 291*, 46ï53.