Simulation of deformation behaviour of Aluminium 7075 during Equal Channel Angular Pressing (ECAP)

Harrison Shagwira [1], *Japheth* Obiko[2,3], *Fredrick* Mwema[4*], and *Tien-Chien* Jen[4]

[1] Department of Mechanical and Industrial Engineering, Masinde Muliro University of Science & Technology, Kenya
[2]Department of Mining, Materials and Petroleum Engineering, Jomo Kenyatta University of Agriculture & Technology, Nairobi, Kenya
[3] School of Chemical and Metallurgical Engineering, University of Witwatersrand, Private Bag 3, Johannesburg, 2050, South Africa
[4] Department of Mechanical Engineering Science, University of Johannesburg, South Africa

Abstract. This paper presents a finite element simulation of equal channel angular pressing (ECAP) since it is one of the most common and successful severe plastic deformation techniques. This study reports the influence of the most significant factors influencing the ECAP technique. Through finite element simulation, the effect of the die geometry, workpiece geometry, and the pressing speed on the effective strain distributions, damage, and pressing loads, were investigated. The influence of the ECAP method on different material models is also presented. Additionally, the prospective expansion and future applications of ECAP are herein highlighted. From the results, the die geometry of a 90° channel imparts the highest strains during ECAP. Additionally, specimens of rectangular geometry are susceptible to cracking and damage as compared to circular samples. It was found that very high processing speeds (>7mm/sec) are undesirable during ECAP since they cause very high internal stresses to the structure of the workpieces. Besides, processing at room temperature can achieve homogeneous strain distribution with minimum sample damage.

1 Introduction

Equal channel angular pressing (ECAP) is one of the most common and successful severe plastic deformation (SPD) techniques. This is because it is possible to process larger samples as compared to other SPD methods such as high-pressure torsion (HPT), and it is possible to process a wide range of materials. As such, a lot of research effort has been dedicated to improving the technique for various materials and applications. There is currently a lot of literature discussing ECAP processing; and these studies take a two-fold approach: (i) to investigate the influence of ECAP on different material models, and (ii) to study the influence of different processing conditions on the ECAP method. In the former approach, studies have

* Corresponding author: fredrick.mwema@dkut.ac.ke

focused on evaluating the stress/strain distribution and homogeneity of material properties such as microstructure and micro-hardness characteristics.

A huge resource of ECAP processing of conventional materials as well as advanced and super-alloys is available. For instance, aluminium 6061 alloy was investigated for microstructure and hardness distribution after a single pass of ECAP and heat treatment by Rominiyi et al. [1]. The microstructural features and dislocation density of ECAP processed AZ91 Mg alloy was studied by Xu et al. [2]. Lei and Zhang [3] investigated the ECAP processing of hot-extruded pure magnesium metal and presented stress/strain and grain refinement maps for an increasing number of passes. An alloy of Mg-10.6Gd-2Ag was processed by the multi-pass ECAP method to obtain a combination of refinement and precipitation strengthening [4].

A lot of studies have been reported on ECAP processing of aluminium and brass alloys as reviewed by Radhi, Aljassani, and Mohammed [5]. Considerable grain refinement of such alloys through ECAP has been reported; for instance, in a study by Elhefnawey [6] the microstructure refinement of 103 nm was achieved during ECAP processing of Al-Mg-Zn after six passes. Other materials processed through ECAP and recently reported in the literature include composites of SiCP/AZ91 [7] and WS2/AZ91 [8]. It can be inferred from the existing literature that most of the ECAP studies have focused on light materials such as aluminium and its alloys, magnesium and its alloys and brass and its alloys. However, a few studies are reporting on super-alloys and advanced materials such as pure titanium [9]–[12], titanium composites and alloys [13]–[15], Niobium and Tantalum [16], etc.

The biggest challenge affecting the severe plastic deformation community has been on achieving uniformity of properties and microstructural refinement [17], [18]. As such, the effort has been on studying the stress/strain distribution during deformation and enhancement of homogeneity in deformation processes. The uniformity of deformation during ECAP can be enhanced by the following two processes.

i. Optimization of the process parameters concerning the property distribution, and
ii. Post-ECAP heat treatment [19], [20].

In terms of process parameters, ECAP is influenced by various parameters such as the die geometry, material models, and the number of passes, and so forth. The combination of these parameters during ECAP processing of materials should be chosen carefully to ensure homogeneity in deformation and distribution of properties such as micro-hardness. Studying stress/strain distribution for a variety of factors is critical in assessing the homogeneous deformation and properties. In this study, different parameters influencing strain/stress distribution during ECAP processing were studied by using finite element simulation modelling.

2 Methods

In this study, DEFORM 3D software was used to conduct finite element simulations. The die was modelled in computer-aided design (CAD) software and then imported into the DEFORM 3D software in an STL file format. A typical die geometry is shown in Fig. 1 in which θ represents the die angle. The die was modelled as a rigid body and the workpiece modelled as plastic. The dimensions of the inner channel of the dies were 25.4 mm by 25.4 mm (square), and the length of the channels were 80 mm by 60 mm. The sample dimensions were 25.4 mm by 25.4 mm by 60 mm long. The number of meshes used for the workpiece was 32,000 chosen on convergence studies not reported in this book. The material model used for the samples was AA7075, which is copper and magnesium dominant aluminium alloy with a tensile strength of 572 MPa, yield strength of 503 MPa and a Vickers hardness of 175. The material has a thermal conductivity of 130 W/m-K, a maximum melting temperature of 630°C, and a specific heat capacity of 0.96 J/g°C.

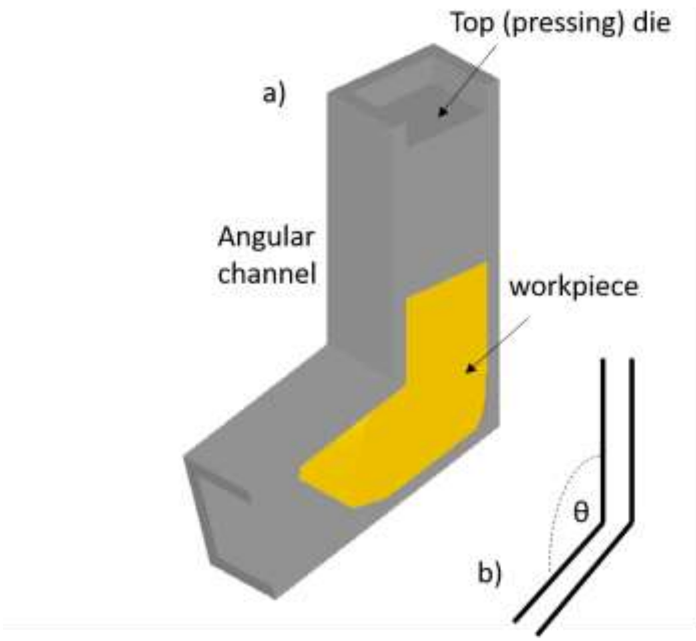

Fig. 1. a) Typical die of the ECAP process and b) showing the die angle in an ECAP die

The sample deformation was by pressing it through the angular channel, and the top (pressing) die velocity was 5 mm/sec. The deformation temperature was done at room temperature (25 °C). The coefficient of friction was 0.05, and the heat transfer coefficient was 45 N/sec/mm/°C. The deformation simulation was based on the Lagrangian incremental and direct iteration method.

3 Results and Discussions

3.1 Influence of the die geometry on the effective strains during ECAP pressing of AA7075

In this case, rectangular channels of varying die angle (θ) were used in the simulation of the ECAP process of AA7075 workpieces. The die angle was increased from 90 to 135° and the results of the three die angles are as shown in Fig. 2. As shown, at a low die angle (90°), the maximum effective strains were obtained, while the lowest effective strains were obtained at the highest die angle (135°) in this study. The results agree with the analytical formulations where the highest strains are obtained at 90°, and at this angle, there is high dislocation density which brings about high strain rates. It was also observed that in each case, the highest effective strains occur at the corners of the rectangular workpiece. As shown in Fig. 2(a), the workpiece deformed at 90° experienced a region of very high strains (marked as **H**), which was not observed in the other cases. On the surface of the sample processed at 105° bands of equal effective strains perpendicular to the pressing die (marked as **B** in Fig. 2(b)) were observed. The peculiar observations for both cases can be related to the load history during the ECAP process, as shown in Fig. 3. In terms of homogeneity, the effective strain distribution was observed to be nearly uniformly distributed on samples processed at 105°, followed by those pressed at 135°. The highest nonuniformity was observed on samples processed at 90°. Heat treatment is usually recommended after ECAP processing of alloys with a 90°-die angle to homogenise the microstructure. Fig. 4 shows the damage prediction during the ECAP processing for the three cases and as it can be seen that the highest damage occurs on the samples experiencing the highest dislocation density.

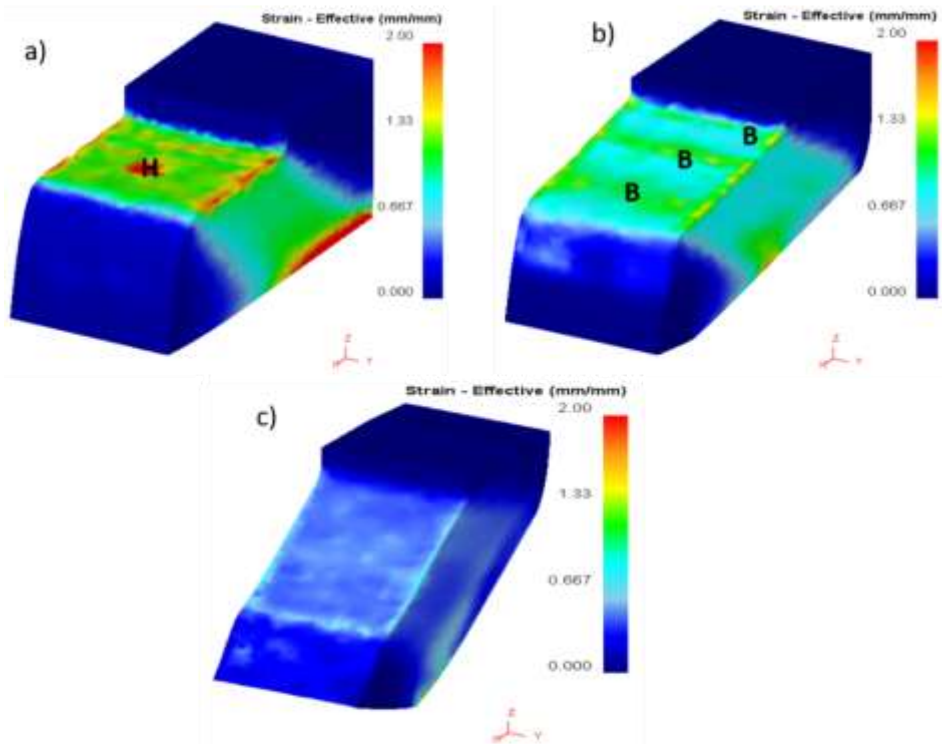

Fig. 2. Showing effective strain distribution on samples processed at different die angles (a) 90°. (b) 105° and (c) 135°. The scale bars for strain distribution are also shown.

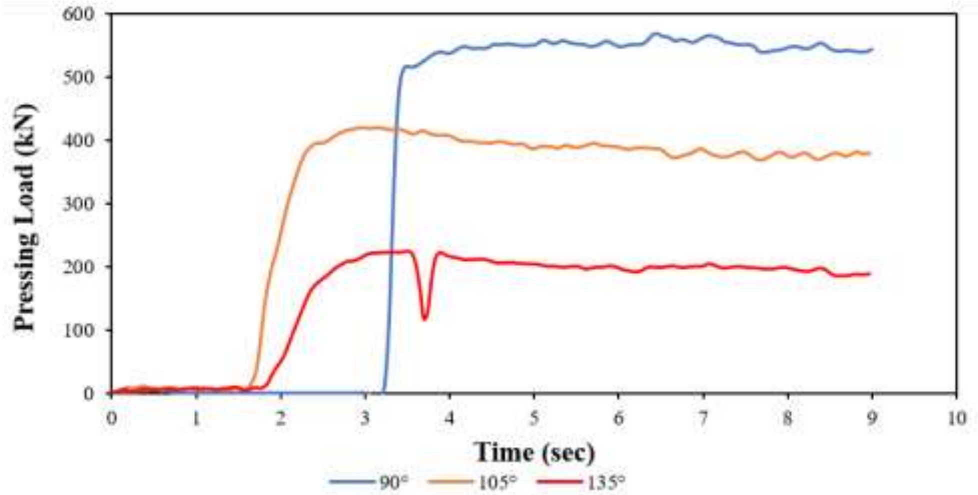

Fig. 3. Applied load history during the ECAP process for the different die angles.

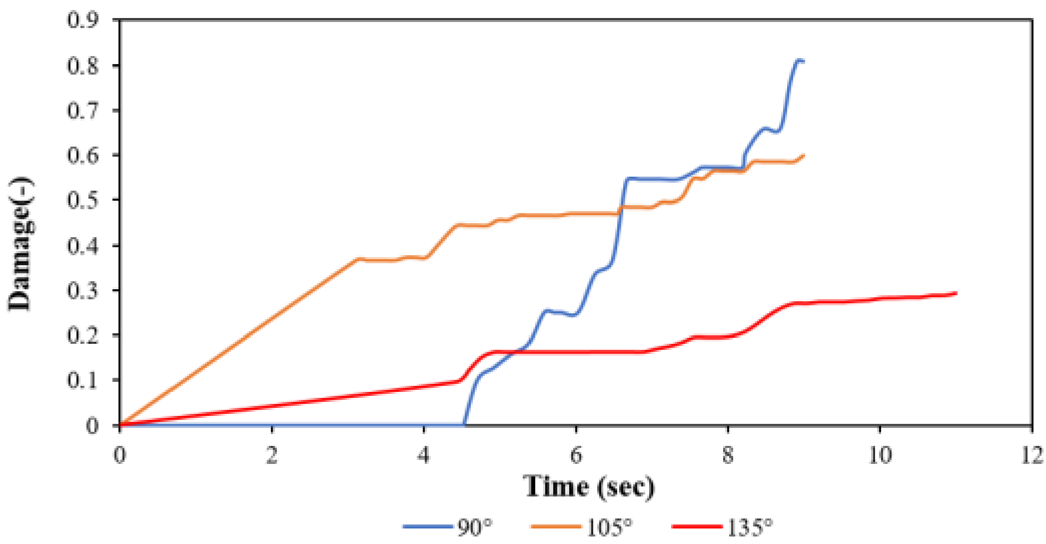

Fig. 4. Showing the damage history of the samples during ECAP for the different die angles

3.2 Influence of the workpiece geometry on the ECAP process

Fig. 5 shows the effective strain distribution on circular and square workpiece geometries processed through ECAP dies of 120°. In terms of intensity, there were no significant differences between the two workpiece geometries. However, the results show that there were slightly high stresses on the corners of the square samples due to the effect of sharp edges on stress tensors. As shown in Fig. 6, there was a relatively higher loading during ECAP processing of square samples than the circular (round) workpiece. The result can be related to the resistance brought about by the sharp corners on the samples. To overcome the resistance, therefore, higher loading is required. As expected, the damage is more in the square samples, as shown in Fig. 7. In one of our laboratory set-ups, a rectangular recycled aluminium piston alloy was processed through the ECAP process using rectangular dies of 120°, and massive damage occurred on the samples (Fig. 8). The sample damage begins via small cracks on the corners of the workpieces due to higher strains experienced in those regions. The cracks are usually perpendicular to the pressing die and grow as the pressing through the die intersection continues.

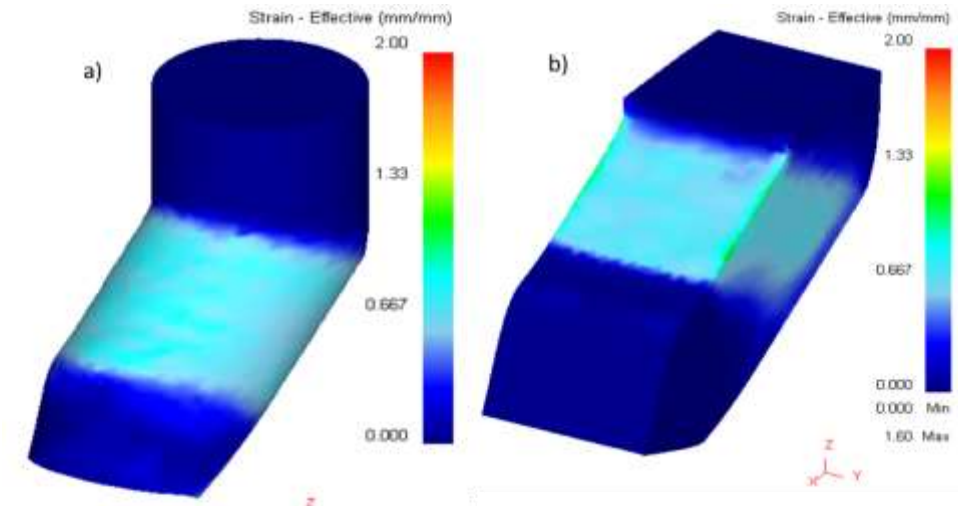

Fig. 5. Influence of die geometry on the effective strains during ECAP pressing of AA7075 a) cylindrical and b) rectangular samples.

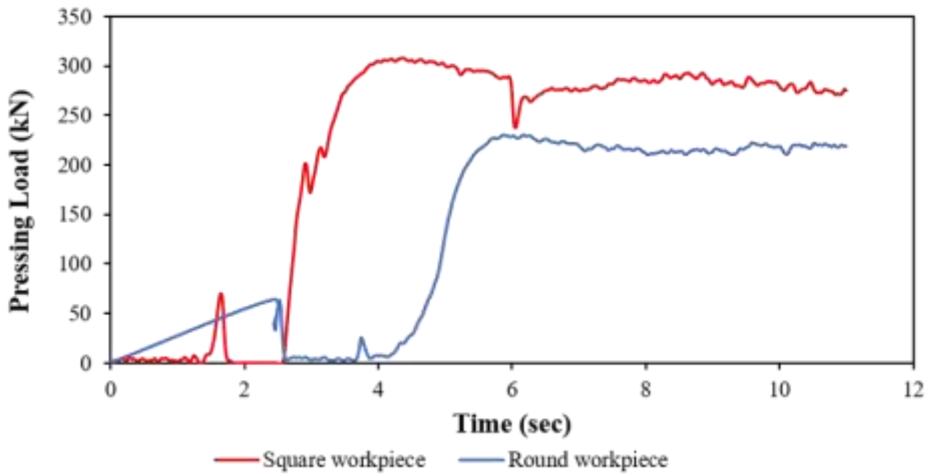

Fig. 6. Pressing load history during ECAP pressing of the square and round geometries of workpieces

Fig. 7. Showing the damage history during ECAP pressing of the square and round workpieces

Fig. 8. Illustrating experimental mechanical damage on the rectangular workpieces during ECAP pressing of recycled aluminium piston alloy.

3.3 Influence of pressing speed

In this case, a die angle (θ) of 120° was used to process AA7075 alloy samples at four different pressing speeds. The speeds used were: 2, 7, 10, and 15 mm/sec. The results of effective strain distribution, pressing load history and damage on the workpieces at the different pressing speeds are shown in Figs. 9, 10 and 11 respectively. As shown, the strain variations with the pressing speed are significant. At pressing speed of 15 mm/sec, there were five strain bands across the surface of the deformed workpiece, 10 mm/sec, there were two strain bands on the workpiece surface, 7 mm/sec, there were four-strain bands on the surface, and 2 mm/sec, there were three strain bands on the deformed sample. As previously observed, the corners exhibited the highest strains due to high-stress concentrations regions. In terms of homogeneity, the workpiece processed at a pressing speed of 10 mm/sec were the most uniform, whereas the specimens processed at 15 mm/sec exhibited the most nonuniform characteristics. Literature shows that high pressing speeds are not desirable during ECAP processing, since they lead to the formation of very high internal stresses and dislocation density generation, and does not allow enough time for relaxation of the structure which results in a large average grain size formations [21]. The internal stresses caused by high pressing speeds into the structure results in cracking and mechanical damage in the workpiece (Fig. 11).

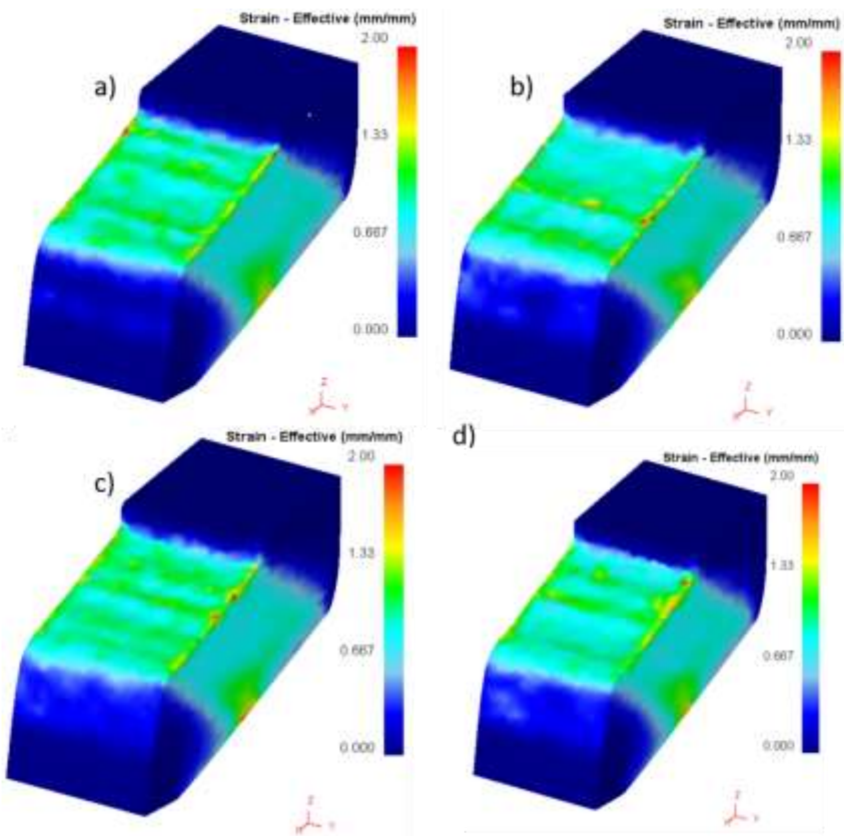

Fig. 9. Effective strain distributions during ECAP processing of AA7075 at varying the pressing speed of a) 15, b) 10, c) 7, and c) 2 mm/sec.

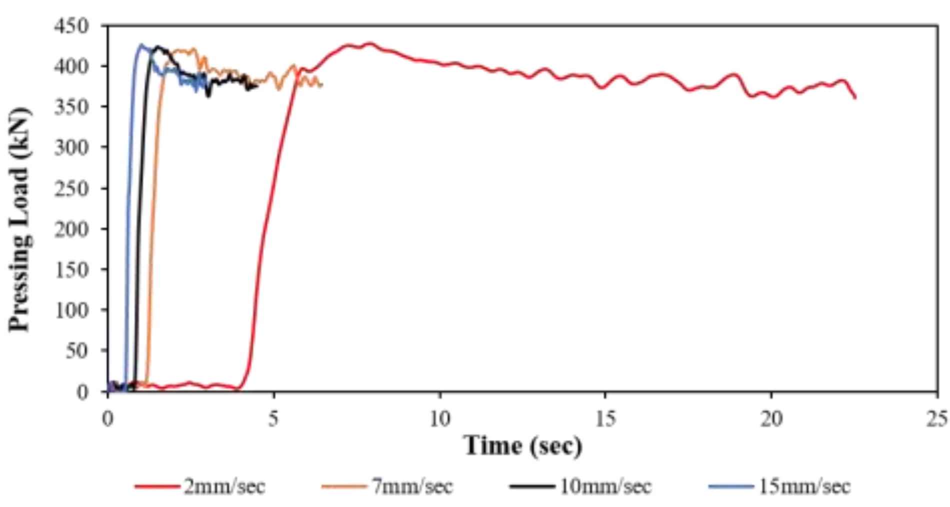

Fig. 10. Pressing load history of AA7075 at different ECAP processing speeds

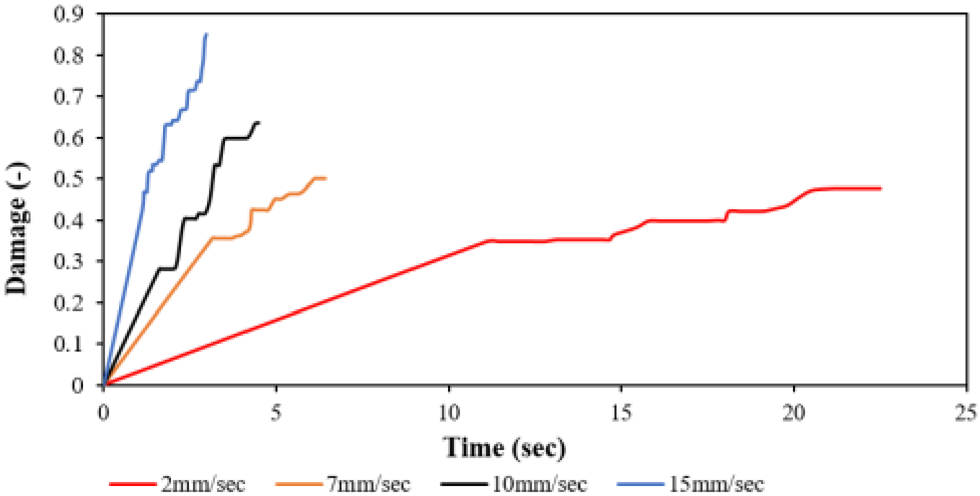

Fig. 11. Damage history during ECAP processing of AA7075 at various top die speeds

3.4 Effect of die temperature on the processing

In this section, the effect of die temperature on the ECAP processing of AA7075 was illustrated. There were four temperatures used in the analysis: 25°C, 100°C, 200°C, 300° and 500°C. As shown in Fig.12, the inhomogeneity in deformation decreased with the temperature of processing, and the best homogenization can be observed at room temperature (25°C). Experimental results showed that severe plastic deformation at room temperature leads to higher refinement as compared to high-temperature processing. Additionally, high-temperature processing leads to precipitation strengthening besides grain refinement and this formation of precipitates may cause inhomogeneous microstructure and grain refinement. Study shows that ECAP processing at high temperatures encourages dynamic recrystallisation resulting in a mixture of elongated and fine grain sizes, and therefore causing non-uniformity in the microstructure [22]. The results on loading and damage on the structure of the specimen, are as shown in Figs. 13 and 14, respectively. There were no much significant differences at different die temperatures.

 https://doi.org/10.1051/matecconf/202337401002

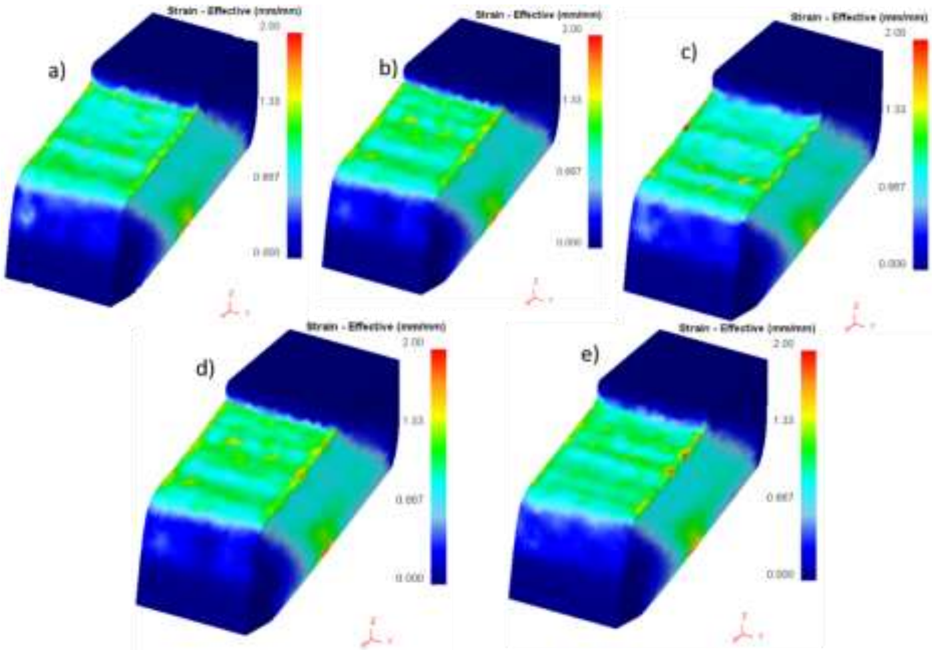

Fig.12. Effective strain distributions of ECAP processing of AA7075 at different die temperatures (a) 25°C, (b) 100°C, (c) 200°C (d) 300°C and (e) 500°C

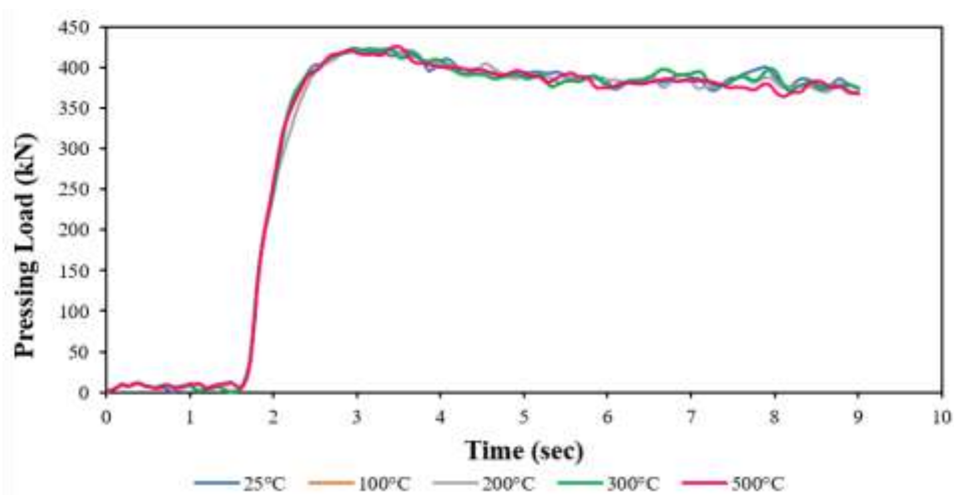

Fig.13. Pressing load history of ECAP processing of AA7075 at a varying die temperature

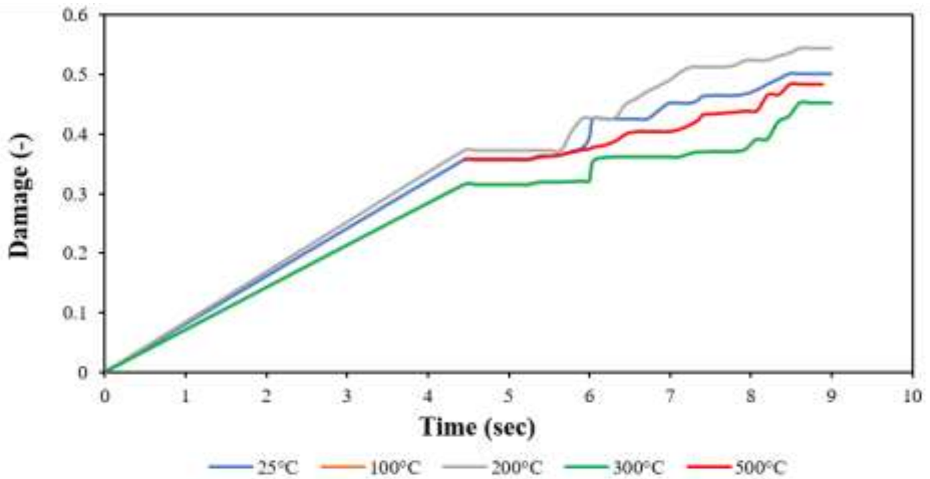

Fig.14. Damage history during ECAP processing of AA7075 alloy at different die temperatures

3.5 Influence of processing on different material models

This section reports on the influence of ECAP on different materials models, five materials used were: copper, brass, steel 1045, stainless steel 304 and AA7075. These material models are used widely in most engineering applications, hence selected for this study. The effective strain distributions for different materials models are as shown in Fig.15. The results show that the materials model influences the deformation behaviour during ECAP processing. As shown, the highest effective strains were obtained in the brass material model, whereas, the lowest occurred in the AA7075 alloy. The higher strain is indicative of the high dislocation motions within the structure of the material, whereas the lower strain in AA7075 is due to the formation of precipitates during ECAP, which hinder further deformation. The strain observations are consistent with load and damage histories, as shown in Figs. 16 and 17.

 https://doi.org/10.1051/matecconf/202337401002

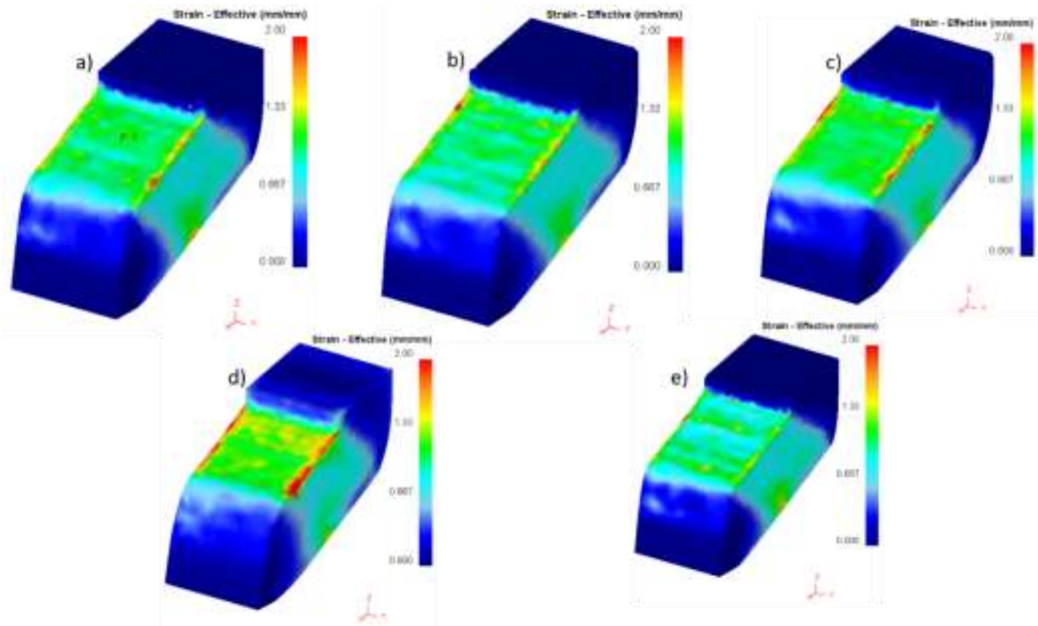

Fig.15. Effective strain distributions during ECAP processing of different materials models a) steel AISI 1045, b) stainless steel 304, c) Copper, d) brass and e) AA7075 alloy

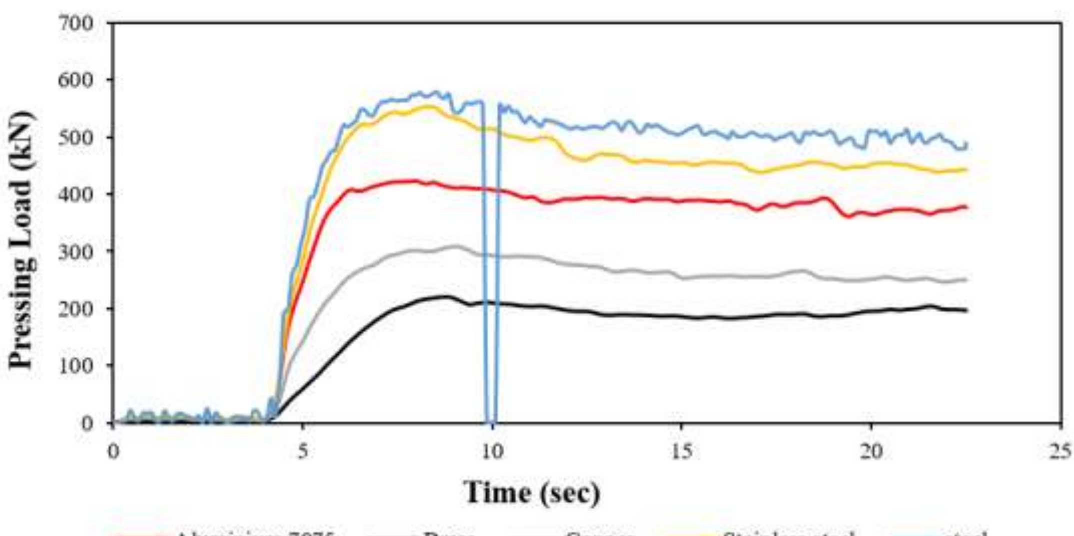

Fig.16. Pressing load history during ECAP processing of various material models

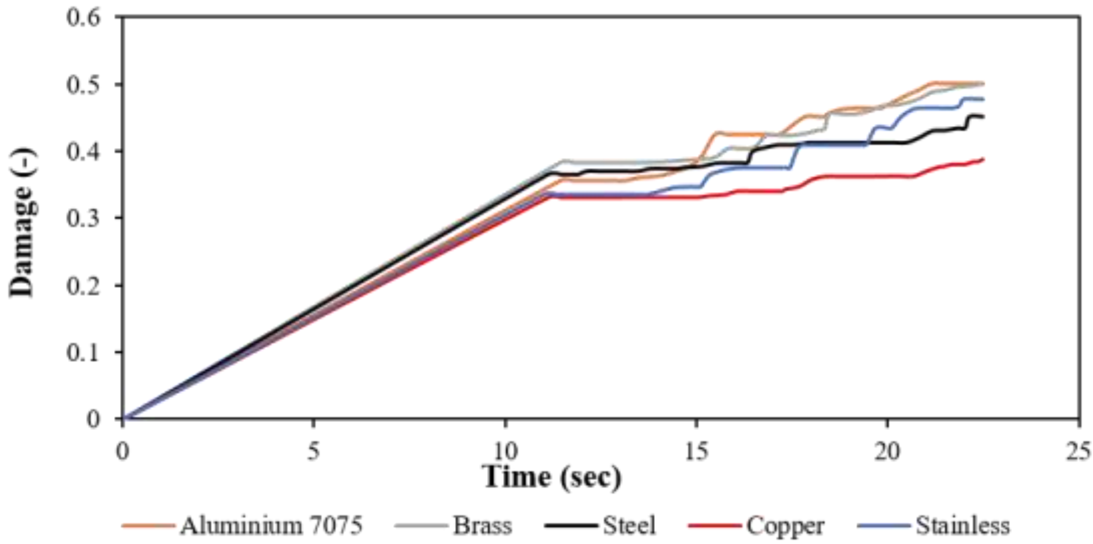

Fig.17. Damage history during ECAP processing of various materials models

3.6 Industrial implications and future directions

Equal angular channel pressing has emerged as one of the attractive severe plastic deformations technologies due to its capability to process relatively larger samples [23]. The technology has the potential to refine bulk materials to ultrafine-grained materials at low homologous temperatures for advanced applications in the modern industry. As alluded earlier, ECAP is used mostly for processing Al and its alloys, magnesium, copper and titanium and their alloys. Titanium materials are attractive for orthopaedic implants, and processing through ECAP enhances their strength as well as ductility for better performance [24], [25]. The flexibility of ECAP process makes it possible to process different shapes of specimens as compared to other SPD processes such as HPT. The ECAP technique can be made continuous, automated, and can be used jointly with other manufacturing processes such as rolling. As such, it will be possible to incorporate the aspects of Industry 4.0 (smart industry concept) such as robotics, augmented reality, artificial intelligence and the internet of things (IoTs).

4 Conclusions

This study reports factors influencing strain distribution, load and damage history during ECAP processing through a finite element modelling procedure. Additionally, the applications and future prospective of ECAP in the smart industry were highlighted. The following important conclusions can be drawn.

- ❖ The die geometry influences the ECAP processing of AA7075 alloys, and 90° imparts the highest strains during ECAP.
- ❖ The configuration of the workpiece determines the strain distribution and damage behaviour of the ECAP processing. Specimens of rectangular geometry are susceptible to cracking and damage as compared to circular samples.
- ❖ The pressing speed directly influences the grain refinement; very high speed is undesirable during ECAP since they cause very high internal stresses to the structure of the workpieces.

- ❖ Processing at room temperature can achieve homogeneous strain distribution with minimum sample damage.
- ❖ Alloys that form precipitates on ECAP refinement were shown to exhibit the lowest strains and therefore difficult to process through the ECAP technique.

References

[1] A. L. Rominiyi, K. M. Oluwasegun, J. O. Olawale, M. B. Shongwe, and A. R. Adetunji, "Effect of post-ECAP aging on the microstructure, hardness and impact behaviour of 6061 Al alloy," Mater. Today Proc., no. xxxx, Jun. 2020.

[2] B. Xu et al., "Microstructure and anisotropic mechanical behavior of the high-strength and ductility AZ91 Mg alloy processed by hot extrusion and multi-pass RD-ECAP," Mater. Sci. Eng. A, vol. 780, no. February, 2020.

[3] W. Lei and H. Zhang, "Analysis of microstructural evolution and compressive properties for pure Mg after room-temperature ECAP," Mater. Lett., vol. 271, p. 127781, Jul. 2020.

[4] Y. Fu et al., "Aging behavior of a fine-grained Mg-10.6Gd-2Ag alloy processed by ECAP," Mater. Charact., vol. 165, no. April, p. 110398, Jul. 2020.

[5] H. N. Radhi, A. M. H. Aljassani, and M. T. Mohammed, "Effect of ECAP on microstructure, mechanical and tribological properties of aluminum and brass alloys: A review," Mater. Today Proc., vol. 26, pp. 2302–2307, 2020.

[6] M. Elhefnawey, G. L. Shuai, Z. Li, M. Nemat-Alla, D. T. Zhang, and L. Li, "On achieving superior strength for Al–Mg–Zn alloy adopting cold ECAP," Vacuum, vol. 174, no. 145, p. 109191, Apr. 2020.

[7] Q. Xu et al., "Enhancement of strength and ductility of SiCp/AZ91 composites by RD-ECAP processing," Mater. Sci. Eng. A, vol. 771, no. October 2019, 2020.

[8] A. Abbas and S.-J. Huang, "ECAP effects on microstructure and mechanical behavior of annealed WS2/AZ91 metal matrix composite," J. Alloys Compd., vol. 835, p. 155466, Sep. 2020.

[9] M. Vishnoi, S. Senthil Murugan, A. N. Veerendra Kumar, and T. G. Mamatha, "Analysis of plastic deformation of Al6063, Magnesium AZ91C and commercially used Titanium alloys using ECAP," Mater. Today Proc., vol. 25, pp. 710–718, 2020.

[10] J. Kawałko et al., "Microstructure of titanium on complex deformation paths: Comparison of ECAP, KOBO and HE techniques," Mater. Charact., vol. 141, no. March, pp. 19–31, Jul. 2018.

[11] M. J. Qarni, A. Rosochowski, and S. Boczkal, "Influence of incremental ECAP on the microstructure and tensile behaviour of commercial purity titanium," Procedia Eng., vol. 207, pp. 1481–1486, 2017.

[12] M. Eftekhari et al., "Processing and characterization of nanostructured Grade 2 Ti processed by combination of warm isothermal ECAP and extrusion," Mater. Sci. Eng. A, vol. 703, no. July, pp. 551–558, Aug. 2017.

[13] Y. Han et al., "Effect of ECAP numbers on microstructure and properties of titanium matrix composite," Mater. Des., vol. 75, pp. 113–119, 2015.

[14] K. Bartha et al., "Effect of the severe plastic deformation by ECAP on microstructure and phase transformations in Ti-15Mo alloy," Mater. Today Commun., vol. 22, no. August 2019, p. 100811, Mar. 2020.

[15] H. F. Li, F. L. Nie, Y. F. Zheng, Y. Cheng, S. C. Wei, and R. Z. Valiev, "Nanocrystalline Ti49.2Ni50.8 shape memory alloy as orthopaedic implant material with better performance," J. Mater. Sci. Technol., vol. 35, no. 10, pp. 2156–2162, Oct. 2019.

[16] B. Omranpour, L. Kommel, V. Mikli, E. Garcia, and J. Huot, "Nanostructure

development in refractory metals: ECAP processing of Niobium and Tantalum using indirect-extrusion technique," Int. J. Refract. Met. Hard Mater., vol. 79, no. October 2018, pp. 1–9, 2019.
[17] F. M. Mwema, T. O. Mbuya, E. T. Akinlabi, P. A. S. Reed, and J. O. Obiko, "Data on the effect of high-pressure torsion processing on secondary cast Al-10%Si- Cu piston alloy: Methods, microstructure and mechanical characterizations," Data Br., p. 104160, Jul. 2019.
[18] H. Liu et al., "Evolution of Mg–Zn second phases during ECAP at different processing temperatures and its impact on mechanical properties of Zn-1.6Mg (wt.%) alloys," J. Alloys Compd., vol. 811, p. 151987, 2019.
[19] J. Krolo, B. Lela, I. Dumanić, and F. Kozina, "Statistical Analysis of the Combined ECAP and Heat Treatment for Recycling Aluminum Chips Without Remelting," Metals, vol. 9, no. 6, p.660, 2019.
[20] M. El-Shenawy, M. Ahmed, A. Nassef, M. El-Hadek, B. Alzahrani, Y. Zedan, and W. El-Garaihy, "Effect of ECAP on the Plastic Strain Homogeneity, Microstructural Evolution, Crystallographic Texture and Mechanical Properties of AA2xxx Aluminum Alloy", Metals, vol. 11, no. 6, p. 938, 2021.
[21] K. V. Ivanov and E. V. Naidenkin, "Effect of the velocity of equal-channel angular pressing on the formation of the structure of pure aluminum," Phys. Met. Metallogr., vol. 106, no. 4, pp. 411–417, Oct. 2008.
[22] Y. Tan, W. Li, W. Hu, X. Shi, and L. Tian, "The effect of ECAP temperature on the microstructure and properties of a rolled rare earth magnesium alloy," Materials (Basel)., vol. 12, no. 9, 2019.
[23] K. O. Sanusi, O. D. Makinde, and G. J. Oliver, "Equal channel angular pressing technique for the formation of ultra-fine grained structures," S. Afr. J. Sci., vol. 108, no. 9–10, pp. 1–7, 2012.
[24] M. J. Qarni, G. Sivaswamy, A. Rosochowski, and S. Boczkal, "Effect of incremental equal channel angular pressing (I-ECAP) on the microstructural characteristics and mechanical behaviour of commercially pure titanium," Mater. Des., vol. 122, pp. 385–402, 2017.
[25] W. M. Mwita, E. T. Akinlabi, and K. O. Sanusi, "Performance and Prospects of Severe Plastic Deformation for Effective Biomedical Titanium Alloys," J. Mod. Mater., vol. 5, no. 1, pp. 8–23, Feb. 2018.