



A new severe plastic deformation method: thin-walled open channel angular pressing (TWO-CAP)

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Abstract

In this study, a novel severe plastic deformation method, named as thin-walled open channel angular pressing (TWO-CAP), was developed and applied to AZ31 magnesium alloy beams in U-type cross-sectional shape. First of all, the principles of the method with all parameters were determined, and the analytical model of the system was generated, and then the study was supported with the numerical analysis. Then, a proper experimental setup was established by considering theoretic outputs. After that, AZ31 magnesium alloy specimens were machined from bulk material in U-type shape as to fit the die channel, and then these specimens were annealed and pressed along the TWO-CAP die. Following the experimental studies, the specimens were tested in order to define the changes in mechanical and microstructural properties. In this stage, the tension test and hardness test were applied to determine the mechanical properties, while optical microscope, scanning electron microscope, energy dispersive spectrometry, X-ray diffraction, and transmission electron microscope analyses were applied to see the changes in microstructure. As a result, an improvement on strength, hardness, and toughness was observed depending on the changes on the microstructure and grain refinement due to the large plastic deformation.

Keywords AZ31 magnesium alloy · Mechanical properties · Microstructure · SEM-EDS · SPD · TEM · XRD

1 Introduction

Severe plastic deformation (SPD) methods gained importance in recent years due to the efficiency in the production of nanomaterials. By the effect of the high stress, ultrafine-grained (UFG) materials can be produced that these materials show high strength to deformation with orientation, precipitation, and dislocations on the internal structure [1]. The most well-known methods of the SPD can be listed as equal-channel angular pressing (ECAP) [2, 3], high-pressure torsion (HPT) [4], repetitive corrugation and straightening (RCS) [5], accumulative roll bonding (ARB) [6], cyclic extrusion compression (CEC) [7],

multidirectional forging (MDF) [8], tubular channel angular pressing (TCAP) or tube channel pressing (TCP) [9, 10], and twist extrusion (TE) [11]. When the methods are extensively investigated, it is seen that all of these are applied to bulk, plate, wire, and tubular materials. After the extensive literature review, it was observed that there is no study about the application of SPD on thin-walled open (TWO) section beams in literature [12]. These beams are commonly used in most section of the industry and structure of several machines; it is believed that doing this study will be useful to researchers in these fields. By this way, the total weight of the beam on the machines will be decreased while their strength is increasing. These materials are named as strength-to-weight ratio efficient materials; that property is vitally important especially for aerospace and automotive industries [13, 14].

In this study, it is aimed to develop an SPD method for TWO cross-section beams, and specimen geometry was chosen as a U-profile beam. By the help of hydrostatic pressure, the U-profile specimen will pass along a linear channel (z-axis) with angular expansion in first pressing and narrowing in second pressing on the cross-section dimension (x-y plane) [15].

The analytical formula was derived for the new method to calculate the equivalent strain which occurs on materials due

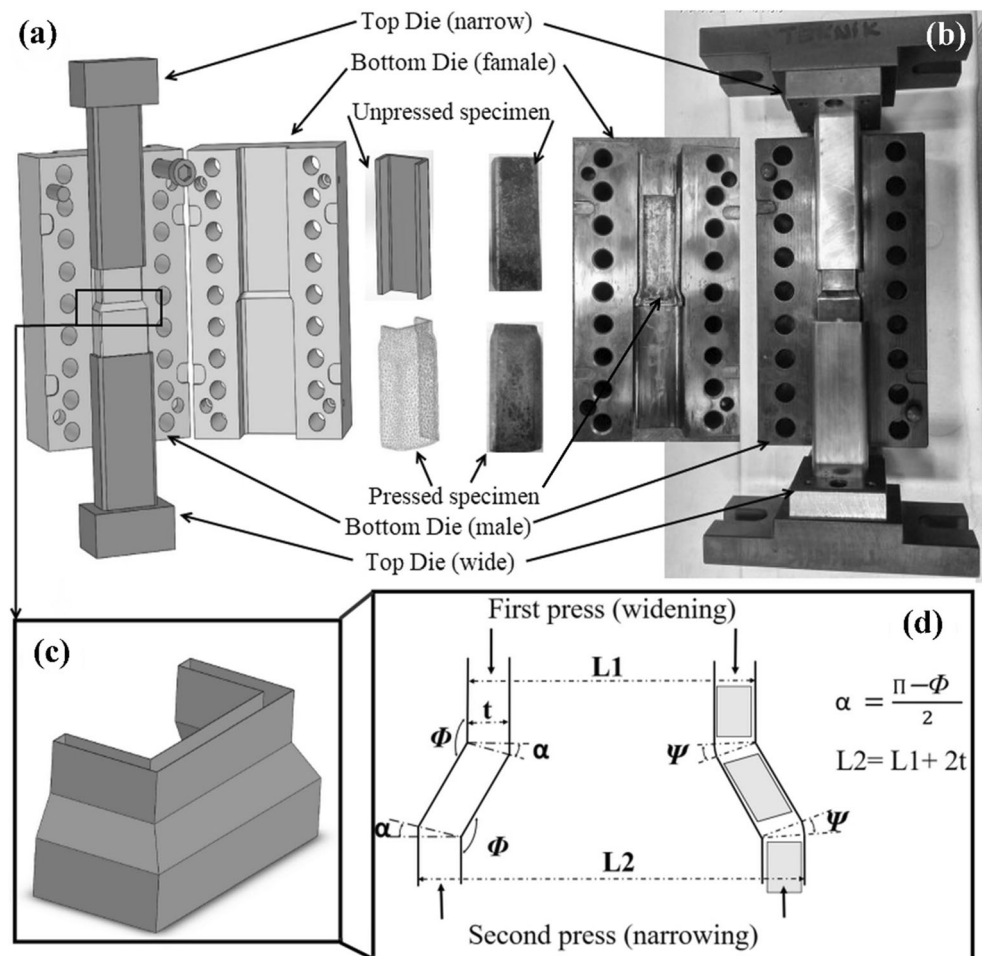
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Fig. 1 3D-CAD model of TWO-CAP dies and specimen (a), original photo of dies and specimen (b), die channel angular section (c), TWO-CAP die parameters (d)



to large plastic deformation [16]. Moreover, a numerical model of the TWO-CAP system was generated, and finite element analysis (FEA) was performed, so the obtained results were compared with the analytical calculations and experimental results. On the other hand, the microstructural improvements on the specimens were investigated by using an optical microscope (OM), scanning electron microscope (SEM), and energy dispersive spectrometry (EDS) method and, in order to determine the characteristic properties, by the help of the X-ray diffraction (XRD) measurements and transmission electron microscope (TEM) analyses. Lastly, the tensile test and hardness tests were performed on these specimens to determine the effect of the TWO-CAP process on the mechanical properties of the material.

2 Material and method

As a methodology, the analytical calculation of the TWO-CAP method was done in the first step by deriving the equivalent strain equation. Then, a simulation study was performed for TWO-CAP method; the system was modeled and numerically analyzed

by a finite element method (FEM) software. At this point, the increase in effective strain can be correlated with the increase of the hardness and strength in the experimentally pressed specimen [16]. The validation study was done for TWO-CAP method by comparing the analytical and numerical outputs with the experimental results. As specimen material, AZ31 magnesium alloy was decided due to its popularity with low mass density, super plasticity, and excellent mechanical properties [17, 18]. Improving these properties can make the alloy as a powerful alternative to the other metals in numerous fields. Therefore, the new developed TWO-CAP method was performed in experimental studies in order to increase the mechanical properties of the material by minimizing its grain size under the submicron levels (production of ultrafine grain material). During the TWO-CAP process, all of the specimens were firstly annealed in 450 °C along 3.5 h; then the specimens were pressed up to 4 passes along the channel of the die in approximately 300 °C. After this stage, the specimens were prepared for metallographic and characterization analyses by abrasive cutting, grinding, polishing, and etching processes. Then the microstructural imaging was performed by using the OM and SEM device while the elemental and structural analysis was performing EDS, XRD,

and TEM instrumentations. Also, tension test specimens were precisely prepared by the help of the EDM (wire erosion) method and tested based on the dimensions specified in ASTM E8 sub-size standard. Lastly, in order to define the effect of the pass number on hardness property, Vickers (HV) test method was applied to the specimens.

2.1 Analytical calculation

The analytical formula of the TWO-CAP method for the equivalent strain can be derived by using the von Mises equation [16, 19] and the geometrical parameters of Fig. 1.

$$\varepsilon_{eq} = \left[\frac{2 \left[\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2 + \frac{\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{xz}^2}{2} \right]}{3} \right]^{1/2} \quad (1)$$

$$\gamma = 2 \cot \left(\frac{\Phi}{2} + \frac{\psi}{2} \right) + \psi \operatorname{cosec} \left(\frac{\Phi}{2} + \frac{\psi}{2} \right) \quad (2)$$

$$\varepsilon_{eq} = 2N \left[\frac{4 \cot(\Phi/2)}{\sqrt{3}} + \frac{2(\varepsilon_x^2 + \varepsilon_y^2)}{\sqrt{3}} \right]^{1/2} \quad (3)$$

For this study, N is pass number, $\varepsilon_y = \gamma_{xy} = \gamma_{yz} = 0$, while the channel angle Φ is 150° and corner angle ψ is 0° . In Eq. 3, the first part represents the generated shear strain (γ_{xz}), while the second part is principal strains in the x-y plane. In here, $\varepsilon_x = \ln(L_2/L_1)$ is the lateral strain, while $\varepsilon_z = \ln(H_2/H_1)$ is the longitudinal strain, and their absolute values are equals to each

other. The wall thickness remains constant during pressing operations, so the strain in the y-axis (ε_y) equals to zero. This state verifies the conservation of the volume theory in plastic deformation ($\varepsilon_x + \varepsilon_y + \varepsilon_z = 0$). As a comparison, the obtained equivalent strain value by applying the TWO-CAP process is higher than the classical ECAP process due to the effect of the principal strains [16].

2.2 Numerical study

TWO-CAP die is composed of four parts: two parts (male–female) bottom die and two punches (top die) in which one of them is narrow and the other one is wide (Fig. 1). The bottom die has two channels along the same direction with equal channel thickness of 3 mm, and they are connected at the center with 150° channel angles. The U-type specimen also has dimensions of 100 mm in height and 30 mm in length at web and 15 mm in length at flanges with 3 mm at wall thickness. The expansion and narrowing occur at both of the flanges and web section of the specimen along with pressing. Due to the two-axis tension and compression, maximum strain occurs at the corner of the U-type specimen that is an occasion of the fact that the more strain means, the more hardness and strength at the critical areas.

At the below (Fig. 1a,b), all part of the TWO-CAP method is schematically presented together with the CAD model and original images. The unpressed and pressed specimens are also shown between the dies as a comparison first and final shapes. In Fig. 1c, the channel angular passing (CAP) section is illustrated by the help of the CAD model; shown here is the expansion and narrowing operation of the specimen that is in U-profile

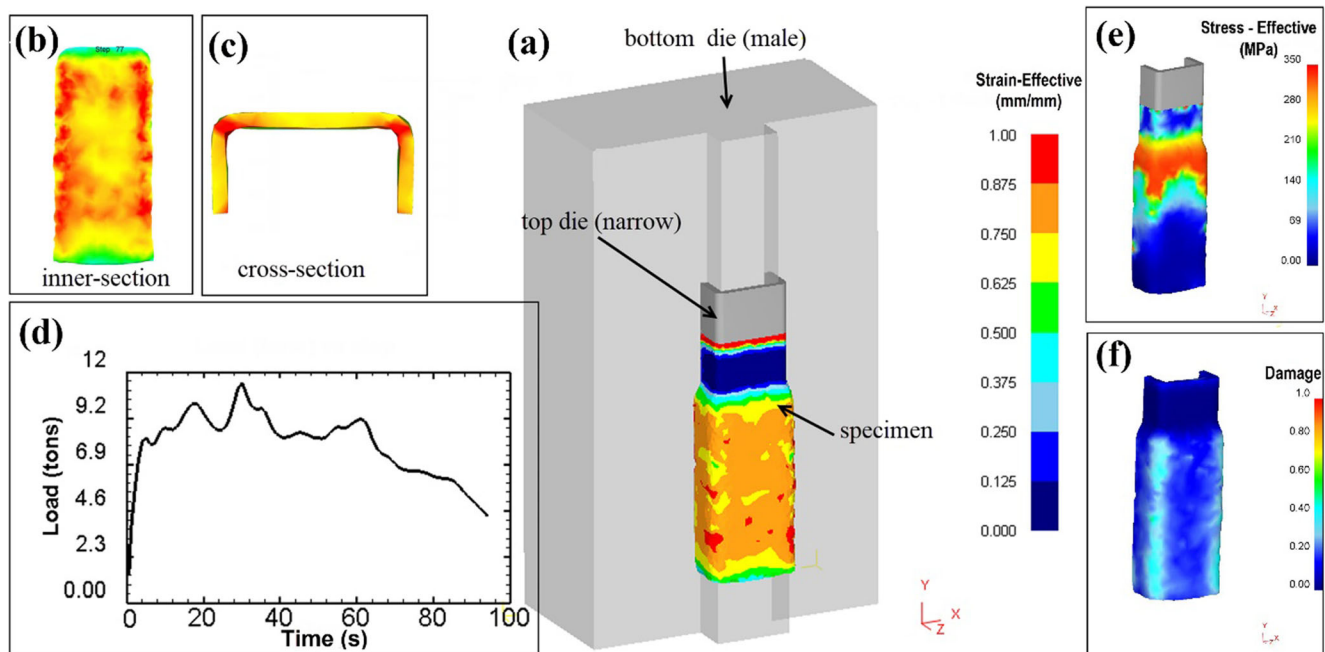


Fig. 2 Numerical analysis results, strain distribution: (a) while specimen pressing with dies (b) inner-section plane of the web, (c) cross-section plane, (d) load versus step (time) graph, (e) effective stress distribution, (f) damage distribution on the specimen

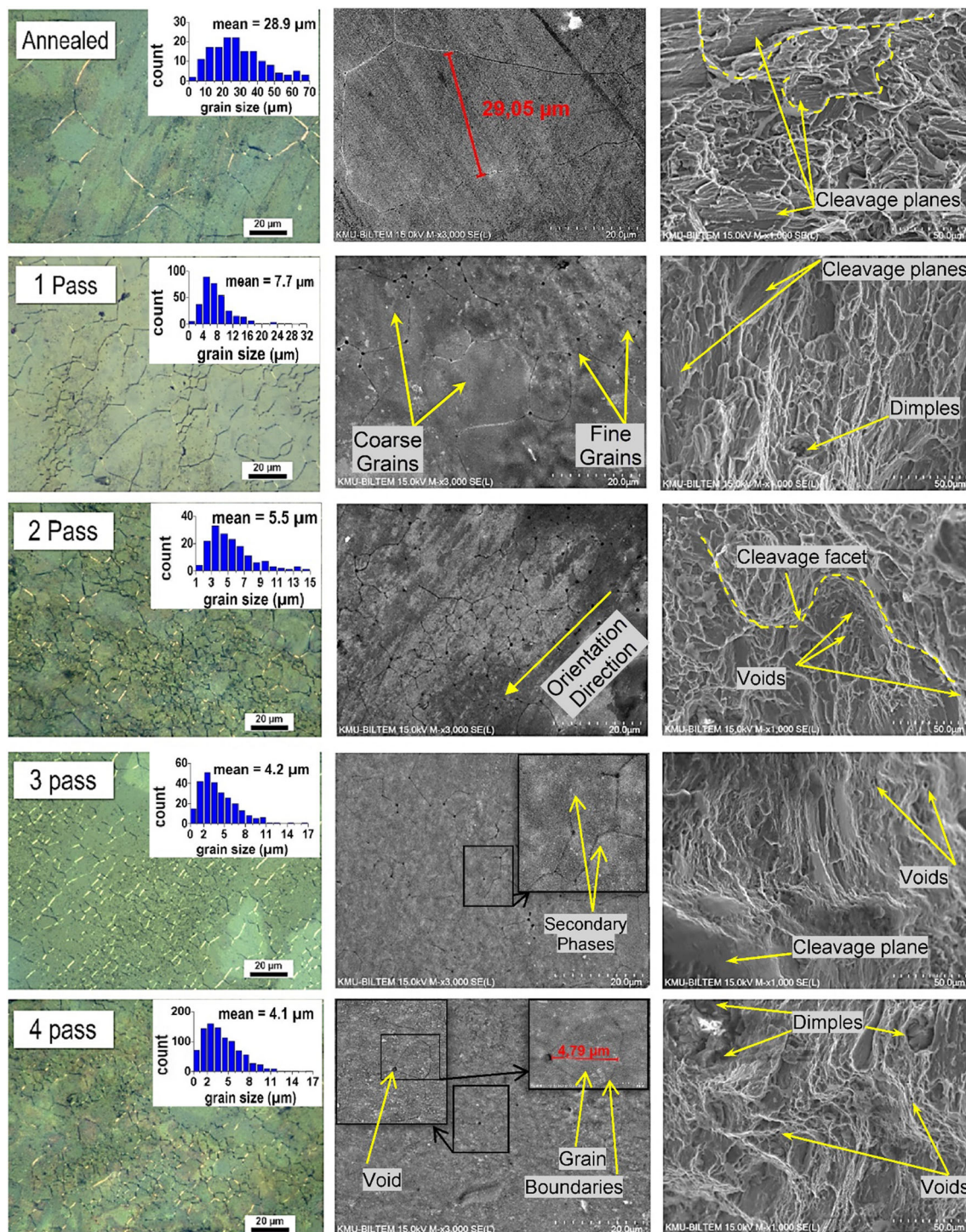
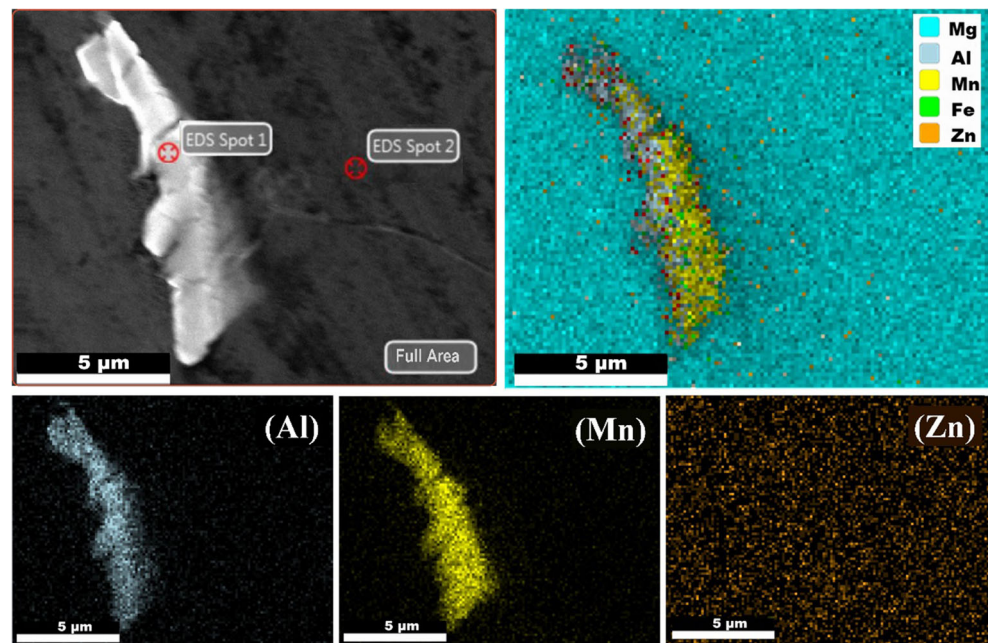


Fig. 3 Microstructure images of AZ31-magnesium alloy from annealed to 4 passes: OM images, 500x of the inner surface and grain size distribution graphs (left column); SEM images, 3000x (middle column); and SEM fractography, 1000x after the tensile test (right column)

shape without any changes on the wall thickness. Fig. 1d also displays the die parameters of the TWO-CAP, where channel angle is $\Phi = 150^\circ$, corner (or curvature) angle is $\psi = 0^\circ$, and refraction angle (it is a dependent parameter that is formulated in Fig. 1d to preserve the wall thickness) is $\alpha = 15^\circ$. Also, initial

web length is $L_1 = 30$ mm, and half-pass web length is $L_2 = L_1 + 2t = 36$ mm. Lastly, the friction coefficient between the dies and workpiece was taken 0.08 because it is the value of the solid lubricant under the press-fit test; it was used in the experimental application of TWO-CAP.

Fig. 4 EDS mapping and elemental analysis of annealed AZ31 alloy



2.3 Experimental study

Experimental studies can be classified in three stages, the first one is the preparation of specimen and annealing, the second one is the pressing operation with TWO-CAP die, and lastly, testing of the specimen taken from the pressed material.

The specimens were manufactured by electro-discharge machining (EDM) operation from bulk material (AZ31 magnesium alloy) in U-profile shape. It has the same dimensions of the numerical model, which are 100 mm height, 30 mm length, 15 mm width, and 3 mm wall thickness. After that, the specimens were annealed 450 °C along 3.5 h in order to homogenize the grain sizes and relieve the residual stresses.

After the annealing process, the specimen was pressed along the TWO-CAP die with constant speed (1 mm/s) and

temperature (300 °C). In TWO-CAP process, one pass is composed of two pressing steps; along the first step, the cross-sectional dimensions of the specimen are enlarged from 30×15 mm to 36×18 mm due to 150° channel angle (Φ), but along the second step, it returns to original dimension again (as seen in Fig. 1). Therefore, the initial dimensions are preserved, which is the essential rule of all repetitive-SPD methods. This act provides the repetition of the pressing operation to the desired pass number for the new generated methods.

3 Results and discussion

In this section, numerical and experimental results will be given by identifying the relation with each other. In numerical analysis part, the finite element analysis (FEA) results will be

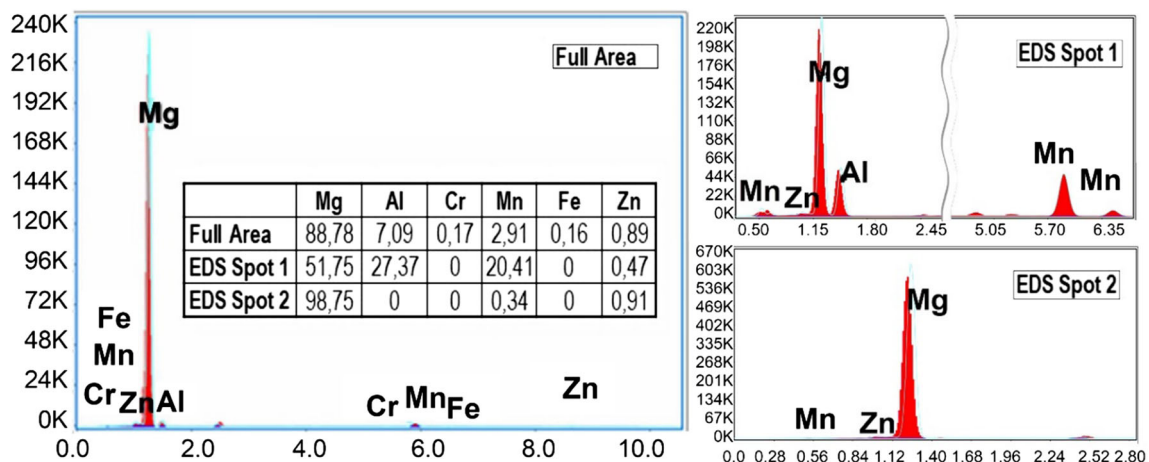


Fig. 5 EDS pattern of full area and spots with a weight ratio of elements

Table 1 The chemical composition of AZ31 alloy in weight %

	Al	Zn	Mn	Si	Cu	Ni	Fe	Mg
Wt.(%)	3.0	0.75	0.68	0.01	0.002	0.001	0.004	Balance

presented by comparing the changes in the effective strain, stress, and applied force and their extremely occurred regions. Then, the effects of the TWOCAP process respectively on microstructure and on the mechanical properties will be given as experimental results. OM, SEM images with EDS, and XRD result will be presented with the changes in their values by the pass number.

3.1 Analytical and numerical analysis results

According to the analytical calculation by using the newly derived equation, the total equivalent strain gain becomes 0.91 after the one pressing (half pass) while 1.82 after one pass. The one pressing value obtained from analytical calculation verifies the numerical strain result, which is illustrated in Fig. 2; in here, the strain distribution on the pressed specimen is almost homogeneous with the average value of 0.85. The differences in strain values between analytical and FEA results are 6.5%, which is a proper value for these types of studies, and it is acceptable.

In numerical analysis results, investigation of the increase in the effective strain on the specimen was the first aim due to the direct relation with the mechanical properties of the material. As shown in Fig. 2, the TWO-CAP process has high efficiency with the high strain on all section of the specimen. Moreover, the more strain occurrence at the corners also has a positive effect on the specimen with the mechanical endurance to failures. Secondly, damage on the specimen was determined during the pressing operation, which is essential for the safety of the material versus fracture. The most damage was expectedly seen on the corner section with the maximum value of approximately 0.4 ($D < 1$), which shows the process safely for material, and there is no

damage on the specimen (Fig. 2f). Then, the effective stress was observed on the specimen during all steps and compared with the applied loads. It was observed that the most stress occurs when the specimen is passing from the angular regions. The validation of the numerical model also was done by comparing the applied load with the experimental pressing load, and similar results were obtained (Fig. 2d). Once, the model was verified with the analytical results in term of the effective strain.

3.2 Effect of TWO-CAP on microstructure

In the material characterization study, three analysis methods, OM, SEM-EDS, and XRD methods, were used to determine the change on the microstructure of the specimens due to the effect of the TWO-CAP process. Grain size analysis and their distributions according to pass number were determined by using an optical microscope device and its software: NIS Element Basic Research, according to ASTM E112–13 standard. In Fig. 3, left column, the differences of the microstructure depending on the pass number were seen clearly for each specimen. While the grains were coarse and more homogeneous on the annealed specimen, the decrease of grain sizes and the orientations are seen in the TWO-CAP applied specimens similar to the literature studies [20, 21].

Therefore, while the grain size was measured 28.9 μm in the annealed specimen, this value decreases to 4.1 μm for four passed specimens (Table 2). The distribution of the grain size versus frequency was also shown on each OM images. Only the OM analysis shows the efficiency of the new developed TWO-CAP method on the grain refinement. The improvement on the microstructure by the increase of the pass number was also verified by taking SEM images from the inner surface of the specimens (Fig. 3, middle column).

Then, the SEM fractography was performed after tension tests to analyze the fracture surface of the specimens (Fig. 3, right column). On these images, the fracture analyses were performed, and it was observed that while the annealed

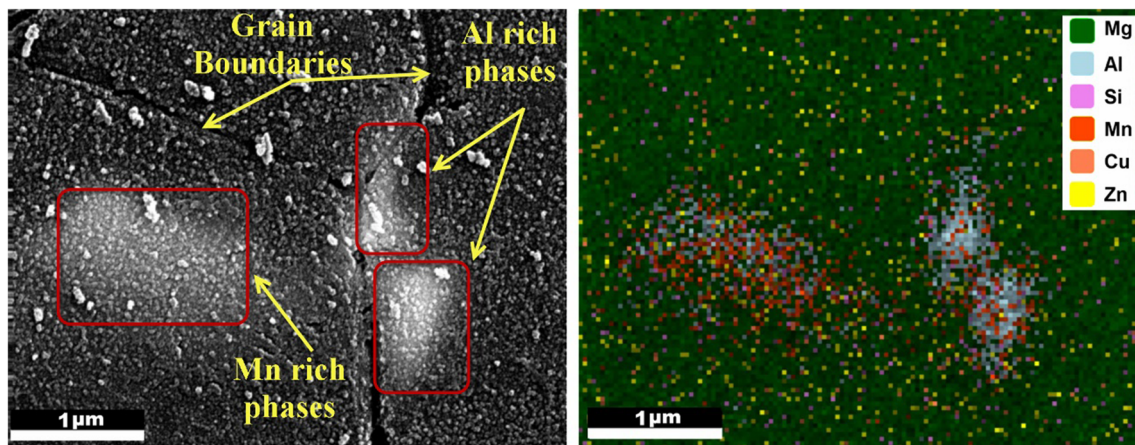


Fig. 6 EDS mapping TWO-CAPed AZ31 with secondary phases and grain boundaries

Table 2 Mechanical and microstructural properties of the all AZ31 specimens

	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation at break (%)	Toughness (MJ/m ³)	Hardness (HV)	Crystal size (nm)	Grain size (μm)
Annealed	52,1	227,7	15,3	20,4	55,2	64,8	28,94
1 pass	136,1	255,2	12,8	28,3	59,4	41,1	7,70
2 pass	146,8	260,1	12,7	28,4	62,2	41,1	5,52
3 pass	161,7	264,3	12,1	28,0	63,3	38,8	4,17
4 pass	172,4	283,2	14,9	37,9	65,4	38,4	4,05

specimen has wide cleavage planes before pressing, voids and dimples took place extremely on the surfaces after the four passes of the TWO-CAP process. This state can be related to the decrease of the grain size with the increase of the pass number.

Lastly, SEM-EDS analysis was done to specimens to perform elemental and phases analyses; by this way, the primary phase (matrix α -Mg) and the secondary phases (Al₁₈Mn₅) were determined on the specimens accompanied by the chemical composition of the elements. The SEM and EDS results of the AZ31 magnesium alloy are presented in Figs. 3, 4, and 5.

In Fig. 4, an intermetallic phase (in micron size) was handled and investigated, and the distribution of the element showed both composed and separate images. As seen in the SEM-EDS results, secondary phases contain mostly Al and Mn elements and, in the negligible ratio, Zn, Fe, Cu, and Si under the 1% weight ratio (Fig. 5).

The chemical composition of AZ31 alloy in weight percent (wt.%) is given in Table 1. The composition does not change in the alloy after the TWO-CAP process.

In Fig. 6, SEM-EDS mapping results illustrate the grain boundaries and the secondary phases distribution. In somewhere, Al-rich phases is observed, while at the other region, Mn-rich phases were placed under the micron size levels (nano-size particles). The size decrease of the intermetallic phases in nano-size can be related to the effect of the TWO-CAP method, like the effect on the grain refinement.

The XRD study was carried out with D8-ADVANCE device diffractometer using CuK α radiation, and crystallite sizes were calculated from the Scherrer equation [22] and were listed in Table 2. It is determined that the crystallite size decreased from 64.8 nm to 38.4 nm at the end of the four passes, depending on the increase of pass number. The XRD pattern of all specimens with the peak identifications is displayed in Fig. 7. The peaks on the patterns indicate the α -Mg phases, which the indexing was based on the pdf card #01-077-6798.

At the below (Fig. 8), TEM analysis images of the four pass TWO-CAP applied AZ31 alloy are displayed. At the left images, the nanocrystals are shown with the close size to the XRD results, while the SAED pattern shows the effect of the TWO-CAP with high intensity on the crystal structure of

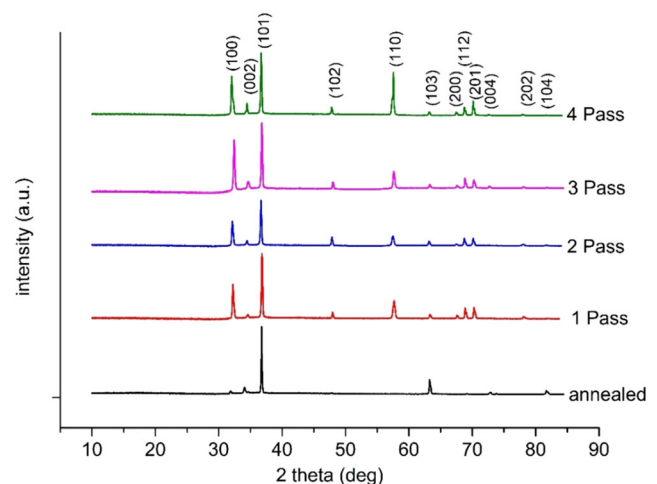
AZ31 alloy which has hexagonal close-packed (HCP) crystal structure.

The right image also shows the lamellas with the accumulation of residual dislocations at the twin boundaries [20, 22, 23]. The increase of the dislocation density also is observed at the boundary lines as a result of the high plastic strain.

3.3 Effect of TWO-CAP on mechanical properties

3.3.1 Tension and hardness test results

In order to accomplish tension tests, the specimens were prepared in compliance with ASTM E8 sub-size standard by using wire EDM from unpressed (only annealed) and TWO-CAPed (annealed + pressed) specimens as shown in Fig. 9a, b, and c. The tension tests were performed with $1 \times 10^{-3} s^{-1}$ strain rate according to the standard, using AGS-X series tensile test device with 100kN capacity. Here, the increase on strength and toughness on TWO-CAPed specimen is clearly seen similar to the literature studies [24, 25]. Figure 9 shows a TWO-CAPed AZ31 workpiece after the extraction of the tensile test specimens (Fig. 9c) and microstructure analysis specimen (Fig. 9b). The hardness test also applied to the cross section of the same specimen (Fig. 9b) after the characterization operations. The tensile test was performed on all sections by taking specimens from

**Fig. 7** XRD patterns and peak identification of AZ31 from annealed to 4 passes

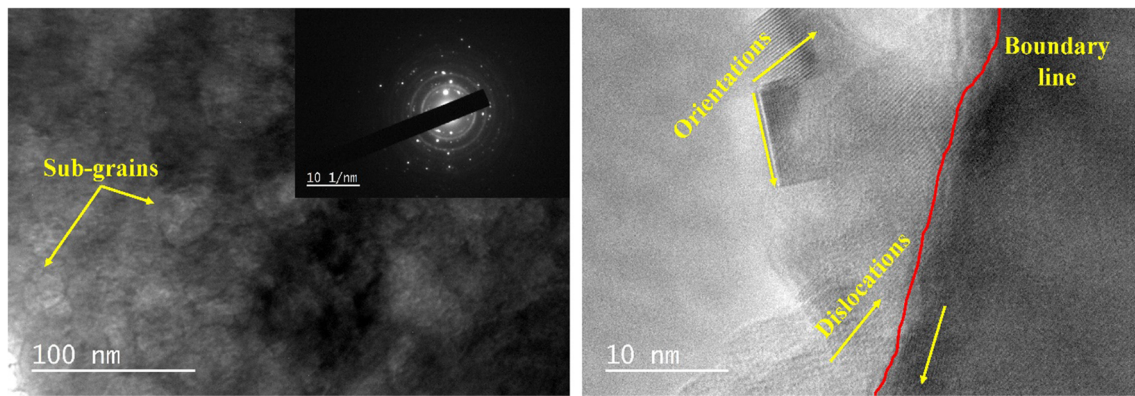


Fig. 8 TEM images with a SAED pattern of the 4 passed AZ31 magnesium alloy

flanges and web of the U-profile, and nearly the same stress-strain graphs were obtained from all regions.

This state shows that the TWO-CAP method improves the mechanical properties at all sections of workpiece homogeneously depending on the microstructural improvements. The average of the three tension test results (Fig. 9c) was accepted as the final result of the passed specimen and the stress-strain curves displayed in Fig. 10. Due to the one-direction tension, maximum shear stress occurs at the plane with 45° tension direction, so the fracture begins in this plane [26]. This state was observed at the tensile test specimens both front and side surfaces at fracture sections (Fig. 9c, e).

As seen in the engineering stress-strain curves in Fig. 10, the elongation decreases at the first three passes while it increases nearly to the value of the annealed specimen after the four passes.

It can be commented as the coexisting of inhomogeneous microstructure with coarse grains and ultrafine grains, and it tends to fail along the boundary of two different regions with different grain size. As a result, the material just reached to stable structure with new fine grains after four passes [27]. By calculating the under area of the curves, it can be seen that the toughness value increases with the pass number, especially after the four passes depending on the stress and elongation.

By the effect of the new SPD method TWO-CAP, the yield strength (YS) significantly increases from 52.1 MPa to 136.1 after the one pass; this increase can be related with the high internal stress and dislocation density. After the one pass, the increase was observed in minimal ratio at the YS and ultimate tensile strength (UTS) while their values noticeably increase at the four passes. This state can be verified with the value of the

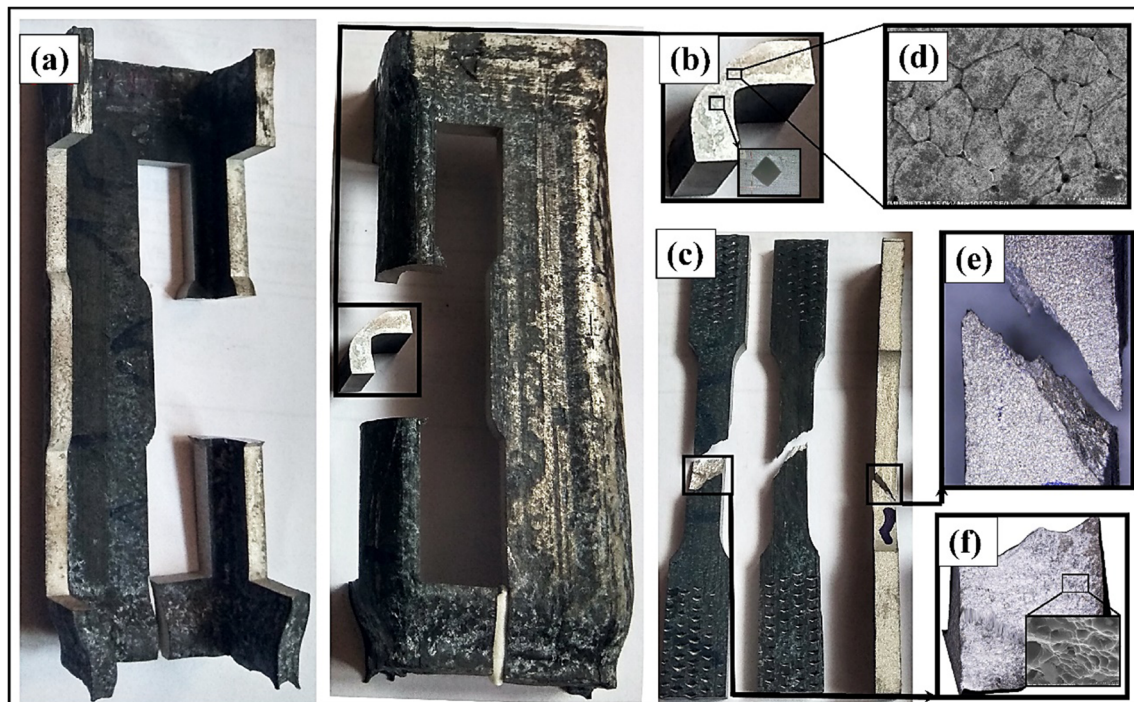


Fig. 9 TWO-CAPed AZ31 after test specimens extracted (a), microstructure analysis and hardness test specimen (b), tensile test specimens (c), grains (d), angled fracture region (e), fracture surface and fractography (f)

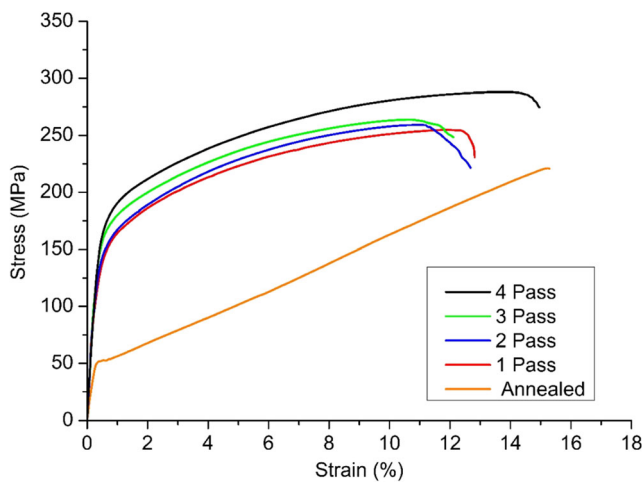


Fig. 10 Engineering stress-strain curve of the 1–4 pass TWO-CAPed and annealed AZ31

grain and crystal sizes, where a high decrease is seen in the first pass, while the negligible decrease occurs until four passes (Table 2).

Hardness property of specimens was determined to utilize Vickers method with the parameters of 10 kgf preload, 30 kgf load, and 6 s duration. The test results have shown that the hardness value is increased to the 65.4 HV after TWO-CAP process while annealed specimen has 55.2 HV (Table 2). The reason for this state can be related to the decrease of the grain size, dislocations, and orientations on the structure of the material [1, 28].

Figure 11 also shows the effect of the pass number on the values of hardness and UTS comparing the crystal sizes. As seen in the figure by the first pass, there is a significant increase in mechanical properties due to the change in the crystal size, whereas in the first three pass, there is a minor increase. However, changes in mechanical properties and crystal size can be accepted stable. However, after the fourth pass, the UTS, YS, toughness, and elongation show a significant increase, and on the contrary, an evenly decrease in the crystal size was not observed. The reason for this improvement in mechanical properties is that

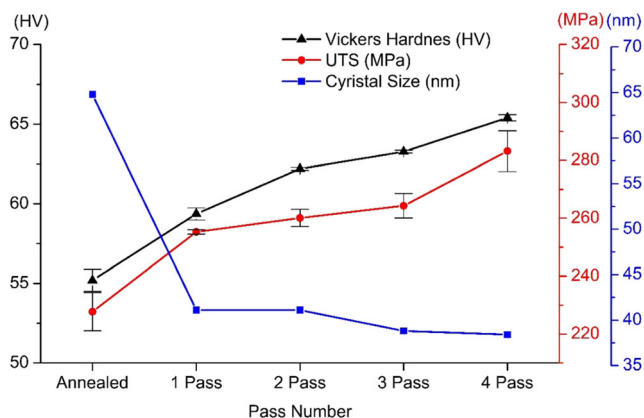


Fig. 11 Comparison of the hardness and UTS values with crystal size for all specimens

the microstructure of the material becomes more regular and stable and it also can be associated with the dislocation densities to the homogenization and circularity in the grains.

4 Conclusion

As a conclusion, a novel SPD method was generated for thin-walled open beams and named as TWO-CAP. The new method was modeled and analyzed with FEA studies, and positive effects of the method were observed on the material properties. Then, the designed dies and specimens were produced, and experimental studies were performed. This study can be accepted as an application of computing techniques in manufacturing operations for thin-walled profiles with manufacturing design and simulation studies. It was detected that the TWO-CAP pressing operation improved the mechanical properties of the materials by affecting the microstructure of them:

- As seen in the results, the process increased the hardness value from 55.2 HV to 65.4 HV (%18.5 increase), similarly UTS from 227.7 MPa to 288.2 MPa (%26.6 increase), and 0.2%YS from 52.1 MPa to 172.4 MPa (%231.3 increase).
- Together with this, the toughness of the material concerning the area under of the stress-strain curve increased from 20.4 MJ/m³ to 37.9 MJ/m³ (%85.8 increase) with the increase in the elongation and UTS after the four passes. These improvements were becoming with the changing in the grain and crystal size, which is verified by the microscopy and XRD studies.
- According to the result of the tests, crystal size decreases with 40.7% at the end of the four passes while the grain size decreases with 86%.
- By the help of the SEM-EDS analysis, the localized secondarily phases around the grain boundaries were observed with the high dislocation density on the microstructure of the materials. The advances on the microstructure also have a positive effect on the mechanical properties of the material as a result of TWO-CAP process.

These outcomes were also verified by the help of TEM analysis images and SAED patterns that the dislocation densities at the boundaries and nanocrystals intensity within HCP crystal structure were determined by this way.

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References

- Valiev RZ (2014) Superior strength in ultrafine-grained materials produced by SPD processing. *Mater Trans* 55:13–18. <https://doi.org/10.2320/matertrans.MA201325>
- Kaya H, Uçar M, Cengiz A, Samur R, Özyürek D, Çalışkan A (2014) Novel molding technique for ECAP process and effects on hardness of AA7075. *Mechanika* 20:5–10. <https://doi.org/10.5755/j01.mech.20.1.4207>
- Özbeyaz K, Kaya H, Kentli A, Şahbaz M, Ögüt S (2019) Mechanical properties and electrical conductivity performance of ECAP processed AA2024 alloy. *Indian J Chem Technol* 26:266–269
- Kawasaki M, Figueiredo RB, Langdon TG (2012) Twenty-five years of severe plastic deformation: recent developments in evaluating the degree of homogeneity through the thickness of disks processed by high-pressure torsion. *J Mater Sci* 47:7719–7725. <https://doi.org/10.1007/s10853-012-6507-y>
- Huang J, Zhu YT, Alexander DJ, Liao X, Lowe TC, Asaro RJ (2004) Development of repetitive corrugation and straightening. *Mater Sci Eng A* 371:35–39. [https://doi.org/10.1016/S0921-5093\(03\)00114-X](https://doi.org/10.1016/S0921-5093(03)00114-X)
- Khatami R, Fattah-alhosseini A, Mazaheri Y, Keshavarz MK, Haghshenas M (2017) Microstructural evolution and mechanical properties of ultrafine grained AA2024 processed by accumulative roll bonding. *Int J Adv Manuf Technol* 93:681–689. <https://doi.org/10.1007/s00170-017-0547-z>
- Richert M, Stüwe HP, Zehetbauer MJ, Richert J, Pippan R, Motz C, Schaffler E (2003) Work hardening and microstructure of AlMg5 after severe plastic deformation by cyclic extrusion and compression. *Mater Sci Eng A* 355:180–185. [https://doi.org/10.1016/S0921-5093\(03\)00046-7](https://doi.org/10.1016/S0921-5093(03)00046-7)
- Bahmani A, Arthanari S, Shin KS (2019) Improved corrosion resistant and strength of a magnesium alloy using multi-directional forging (MDF). *Int J Adv Manuf Technol* 1–13. <https://doi.org/10.1007/s00170-019-04176-1>
- Faraji G, Babaei A, Mosavi Mashadi M, Abrinia K (2012) Parallel tubular channel angular pressing (PTCAP) as a new severe plastic deformation method for cylindrical tubes. *Mater Lett* 77:82–85. <https://doi.org/10.1016/j.matlet.2012.03.007>
- Zangiabadi A, Kazeminezhad M (2011) Development of a novel severe plastic deformation method for tubular materials: tube channel pressing (TCP). *Mater Sci Eng A* 528:5066–5072. <https://doi.org/10.1016/j.msea.2011.03.012>
- Beygelzimer Y, Orlov D, Varyukhin V (2002) A new severe plastic deformation method: twist extrusion. In: *Ultrafine grained materials II*. John Wiley & Sons, Inc., Hoboken, pp 297–304
- Bagherpour E, Pardis N, Reihanian M, Ebrahimi R (2019) An overview on severe plastic deformation: research status, techniques classification, microstructure evolution, and applications. *Int J Adv Manuf Technol* 100:1647–1694. <https://doi.org/10.1007/s00170-018-2652-z>
- Jiang J, Yuan T, Zhang W, Ma A, Song D, Wu Y (2018) Effect of equal-channel angular pressing and post-aging on impact toughness of Al-Li alloys. *Mater Sci Eng A* 733:385–392. <https://doi.org/10.1016/J.MSEA.2018.07.037>
- Kulekci MK (2008) Magnesium and its alloys applications in automotive industry. *Int J Adv Manuf Technol* 39:851–865. <https://doi.org/10.1007/s00170-007-1279-2>
- Şahbaz M (2019) Development of a novel severe plastic deformation method for a thin-walled open section beam: thin-walled open channel angular pressing (TWO-CAP). Dissertation, Marmara University
- Iwahashi Y, Wang J, Horita Z, Nemoto M, Langdon TG (1996) Principle of equal-channel angular pressing for the processing of ultra-fine grained materials. *Scr Mater* 35:143–146. [https://doi.org/10.1016/1359-6462\(96\)00107-8](https://doi.org/10.1016/1359-6462(96)00107-8)
- Lin HK, Huang JC, Langdon TG (2005) Relationship between texture and low temperature super plasticity in an extruded AZ31 Mg alloy processed by ECAP. *Mater Sci Eng A* 402:250–257. <https://doi.org/10.1016/J.MSEA.2005.04.018>
- Dziubińska A, Gontarz A, Horzelska K, Pieško P (2015) The microstructure and mechanical properties of AZ31 magnesium alloy aircraft brackets produced by a new forging technology. *Proc Manuf* 2:337–341. <https://doi.org/10.1016/J.PROMFG.2015.07.059>
- Valiev RZ, Estrin Y, Horita Z, Langdon TG, Zechetbauer MJ, Zhu YT (2006) Producing bulk ultrafine-grained materials by severe plastic deformation. *JOM* 58:33–39. <https://doi.org/10.1007/s11837-006-0213-7>
- Ghorbani A, Zarei-Hanzaki A, Dastranjy Nezhadfar P, Maghsoudi MH (2019) Microstructural evolution and room temperature mechanical properties of AZ31 alloy processed through hot constrained compression. *Int J Adv Manuf Technol* 102:2307–2317. <https://doi.org/10.1007/s00170-019-03321-0>
- Hu H, Qin X, Zhang D, Ma X (2018) A novel severe plastic deformation method for manufacturing AZ31 magnesium alloy tube. *Int J Adv Manuf Technol* 98:897–903. <https://doi.org/10.1007/s00170-018-2179-3>
- Zhou H, Hu L, Sun Y, Zhang H, Duan C, Yu H (2016) Synthesis of nanocrystalline AZ31 magnesium alloy with titanium addition by mechanical milling. *Mater Charact* 113:108–116. <https://doi.org/10.1016/j.matchar.2016.01.014>
- Zhang W, Lu J, Huo W, Zhang Y, Wei Q (2018) Microstructural evolution of AZ31 magnesium alloy subjected to sliding friction treatment. *Philos Mag* 98:1576–1593. <https://doi.org/10.1080/14786435.2018.1447701>
- Fatemi SM, Zarei-Hanzaki A (2017) Mechanical behavior of an ultrafine/nano grained magnesium alloy. *J Ultrafine Grained Nanostruct Mater* 50:6–15. <https://doi.org/10.7508/JUFGNSM.2017.01.02>
- Chapuis A, Wang Z, Liu Q (2016) Influence of material parameters on modeling plastic deformation of Mg alloys. *Mater Sci Eng A* 655:244–250. <https://doi.org/10.1016/J.MSEA.2015.12.067>
- Vaughan MW, Nasim W, Dogan E, Herrington JS, Proust G, Benzerger AA, Karaman I (2019) Interplay between the effects of deformation mechanisms and dynamic recrystallization on the failure of Mg-3Al-1Zn. *Acta Mater* 168:448–472. <https://doi.org/10.1016/J.ACTAMAT.2019.02.010>
- Guo W, Wang QD, Ye B, Liu MP, Peng T, Liu XT, Zhou H (2012) Enhanced microstructure homogeneity and mechanical properties of AZ31 magnesium alloy by repetitive upsetting. *Mater Sci Eng A* 540:115–122. <https://doi.org/10.1016/J.MSEA.2012.01.111>
- Tao NR, Wang ZB, Tong WP, Sui ML, Lu J, Lu K (2002) An investigation of surface nanocrystallization mechanism in Fe induced by surface mechanical attrition treatment. *Acta Mater* 50:4603–4616. [https://doi.org/10.1016/S1359-6454\(02\)00310-5](https://doi.org/10.1016/S1359-6454(02)00310-5)

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