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ORIGINAL RESEARCH PAPER

Effects of the Geometric Profile of Twist Channel Angular Pressing (TCAP) on the Deformation Behaviors and Microstructure Evolution of AL7050 Alloy

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Abstract

Severe plastic deformation processes are used as a method to increase the mechanical strength of metals. One of the new deformation methods is twist channel angular pressing (TCAP). TCAP has been developed based on a combination of twist extrusion processes (TE) and Equal Channel Angular Pressing (ECAP) process. In this paper, the effect of TCAP die geometry on the grain size distribution and plasticity properties using simulation in DEFORM software is investigated. For this reason, dies with internal angles of 90°, 100° and 110°, external (corner) angles of 0°, 10° and 20° and twist angles of 30°, 45°, 60° are used. In addition, the location of the twist channel is examined before and after the ECAP location. The distribution of plastic strain, grain size distribution, and the required punch force for the TCAP process on Aluminum alloy 7050 are extracted in all conditions. The results showed that locating the twist section after ECAP location led to a better microstructure in the billet. Also, die with a twist angle of 45°, an internal angle of 110°, and a corner angle of 0° created the best results; therefore, the grain size decreased from 100μm to 3.67μm.

Nomenclature

β	Twist angle of TCAP die	Ψ	Corner angle of TCAP die
Φ	Angle of ECAP channel	Z	Zener-Holloman parameter
$\dot{\varepsilon}$	Strain rate	T	Absolute temperature
R	Gas constant (8.3145 $K^{-1} J$ mol^{-1})	Q	Activation energy for hot deformation
σ_p	Peak stress	X_{DRX}	Volume fraction of recrystallization
β_d	Avrami constant	d_0	The initial grain size
$A, \acute{n}$, β, α	Arrhenius equation constants	d_{DRX}	Grain size after recrystallization
$m_8, m_5,$	Dynamic recrystallization	h_5, a_{10}, a_8, a_5	Equations constants

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1. Introduction

Aluminum alloys have attracted special attention due to their high strength to weight ratio, ductility, and proper deformability [1, 2]. Aluminum 7050 belongs to the 7xxx alloy series, which is widely used in the aerospace industry to produce components [3]. The widespread application of aluminum 7050 is associated with the mechanical properties and physical properties of this material, the efficiency at high temperature of this material is influenced by microstructure properties and its high strength, and the possibility of increasing it by the appropriate thermomechanical process is another reason to use use this alloy [4]. Severe plastic deformation methods with the aim of enhancing mechanical properties and improving microstructure properties of metals are of interest to researchers and industries. So far, extensive research has been conducted in this field. The Equal Channel Angular Pressing (ECAP), High Pressure Torsion (HPT), Single Step High Pressure Torsion (SIHPT) [5], Twist Extrusion (TE) and more recently, Twist Channel Angular Pressing (TCAP) have received more attention from researchers. The ECAP process is developed by Segal [6] and continued in other studies [7, 8]. Another process called twist extrusion (TE) is first designed by Beygelzimer et al. [9]. Then, a process consisting of two previous processes called TCAP is designed and researched by Kocich et al. [10, 11]. The TCAP process creates more strain than the conventional ECAP method in the billet [12]. TCAP die consists of two parts: TE and ECAP, which is shown in Fig. 1 of the die of this process.

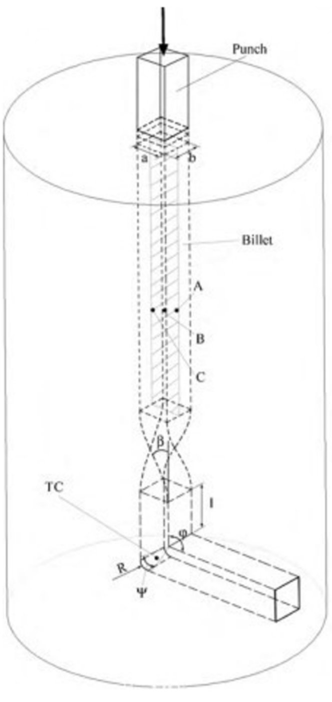


Fig. 1. A view of a TCAP [10].

This die is shown by parameters such as β twist angle, Ψ corner angle (external), Φ angle of ECAP channel (for ease of time in this research is called an internal angle), and R radius of curvature of the corner of the channel. Various research have been conducted in the field of ECAP. Agwa et al. [12] investigated the effect of corner angle, internal angle, and friction coefficient on strain distribution and punch force in the ECAP process. Their results showed that the friction coefficient had the greatest effect on punch force, and at the outer angle (corner), a high strain is inserted into the billet. In 2017, Keshtiban et al. [13] investigated the effect of process parameters and ECAP format on Al-3Mg sheet samples. In this study, three parameters including ECAP internal angle, external corner angle, and friction coefficient are considered as the variables of the analysis. Also, the effect of combining internal angle, outer corner radius, and internal corner radius parameters on punch force and strain in the ECAP process is investigated by Patil et al. [14]. They obtained results related to the parameters of peak force, strain, and strain heterogeneity. The results of this study showed that internal angle had the greatest effect on punch force and strain. In 2018, Reshetov et al. [15] examined titanium extrusion during the twist extrusion process. Also, in this study, a comparison with the HPT process is performed on hydrostatic pressure. The results of this study include an increase of strain-hardening in the twist extrusion process, unlike the high-pressure torsion process, and reducing the need for strain accumulation in achieving the ideal plastic state in the twist extrusion process. Reduction of hydrostatic pressure in the twist extrusion process is also obtained from this comparison. In 2013, Latipov et al. [16] compared twist extrusion under three rounded rectangular, flat rectangular, and elliptical cross-sections. Based on the results of this study, the similarity of stress and strain results in both classical cross-section and circle-oval cross-sections. The results also showed that the elliptical cross-section had fewer apparent defects after the process. In another study, Heydari et al. [17] investigated the effect of die geometry on the twist extrusion process of Al alloy 7050 and material microstructure. In this study, two types of elliptical and rectangular cross-sections with different dimensions and twist angles are considered. The results of the analysis showed that the elliptical cross-section is the best, and 56° is the optimal twist angle. This study revealed that the material had a more homogeneous microstructure when extruded with an elliptical cross-section. In a 2019 study conducted by Mohammad Iqbal et al. [18] on the TCAP process, they investigated and optimized the format of this process for Al 6063 and its validation by experimental results. Their results showed that the billet under the twist angle of 45° and the internal angle of 110°C resulted in the best outcomes in terms of strain and force. In another study, Kocich et al. [10] investigated the TCAP process as a method to increase the efficiency of the severe plastic deformation method. Among the outcomes of this study is an increase in strain values in a pass, which significantly reduces the need to increase the number of passes. In another study, Kocich et al. [19] studied the Twist Channel Multi-Angular pressing process. In this paper, we tried to obtain the effect of die geometry on the equivalent strain; however, the effect of die geometry and changes in the shape of the conventional cross-section on the microstructure of materials has not been discussed. Also, in all the research, the effect of all die parameters such as corner angle on microstructure has not been investigated. The microstructure is another issue that has not been comprehensively reviewed in previous papers and it has been one of the sub-topics in previous papers and has sometimes been briefly investigated. Considering the presented cases and their presence in other processes, it is decided to investigate the effect of twist angle, internal angle and corner angle on an oval-crossed format in this study.

2. Finite Element Analysis

Finite element analysis is validated with the results obtained from the research of Mohammad Iqbal et al. [18]. According to the papers, the elliptical cross-section is considered as the optimal cross-section for the process [16, 17]. According to the studies of other researchers in the field of ECAP and TE process, the dies are designed with three different twist angles of 30°, 45°, 60°, three internal angles of 90°, 100°, and 110°, and three external curvature angles of 0°, 10° and 20°. Also, the twist channel of the die before or after the ECAP location is investigated. The friction coefficient is 0.05, punch speed is 1mm/s, the initial temperature of the process is 300°C, and the heat transfer coefficient between the billet and the die is 0.1N.mm/sec.°C. Due to the convergence of the results based on number of billet elements, tetrahedral elements are considered 70, 500. In Fig. 2, there is a view of the billet with the intended format.

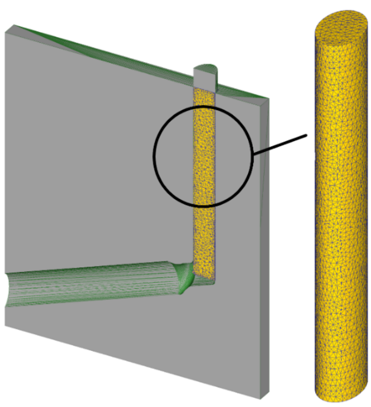


Fig. 2. A view of the meshed billet with the TCAP die.

The Arrhenius equation is widely used to link the strain rate, flow stress, and temperature at high temperatures [20]. The effect of temperature and strain rate on deformation behavior changes is expressed by the Zener-Holloman (z) parameter. In these simulations the Arrhenius equation is used, which is expressed by (1-3) equations.

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

$$\dot{\varepsilon} = AF(\sigma) \exp\left(\frac{-Q}{RT}\right) \tag{2}$$

$$F(\sigma) = \begin{cases} \sigma^{\acute{n}} & \alpha\sigma < 0.8 \\ \exp(\beta\sigma) & \alpha\sigma > 1.2 \\ [\sinh(\alpha\sigma)]^n & \text{for all } \alpha\sigma \end{cases} \tag{3}$$

$\dot{\varepsilon}$ is strain rate in terms of s^{-1}, R is gas constant (8.3145 $K^{-1}J$ mol^{-1}), T is absolute temperature in terms of K, Q is activation energy for hot deformation in terms of Jmol^{-1}, A, $\acute{n}$, β, α, and n are the material constants [21]. For aluminum alloy 7050, the Arrhenius material equation is considered as relation (4):

$$\dot{\varepsilon} = 5.83 \times 10^{18}[\sinh\left(1.239 \times 10^{-2}\sigma_p\right)]^{7.589} e^{\frac{-2.6406\times 10^5}{RT}} \tag{4}$$

Dynamic recrystallization occurs when the dislocations density or strain value in high temperature deformations reaches a certain value. The density of dislocations and strain value is related to strain rate and process temperature. There are various equations for dynamic recrystallization. In these simulations, Avrami's recrystallization equations are used [21].

$$\varepsilon_p = a_1 d_0^{n1} \dot{\varepsilon}^{m5} \exp\left(\frac{Q_1}{RT}\right) + C_1 \tag{5}$$

$$X_{DRX} = 1 - \exp\left[-\beta_d \left(\frac{\varepsilon - a_{10}\varepsilon_p}{\varepsilon_{0.5}}\right)^{kd}\right] \tag{6}$$

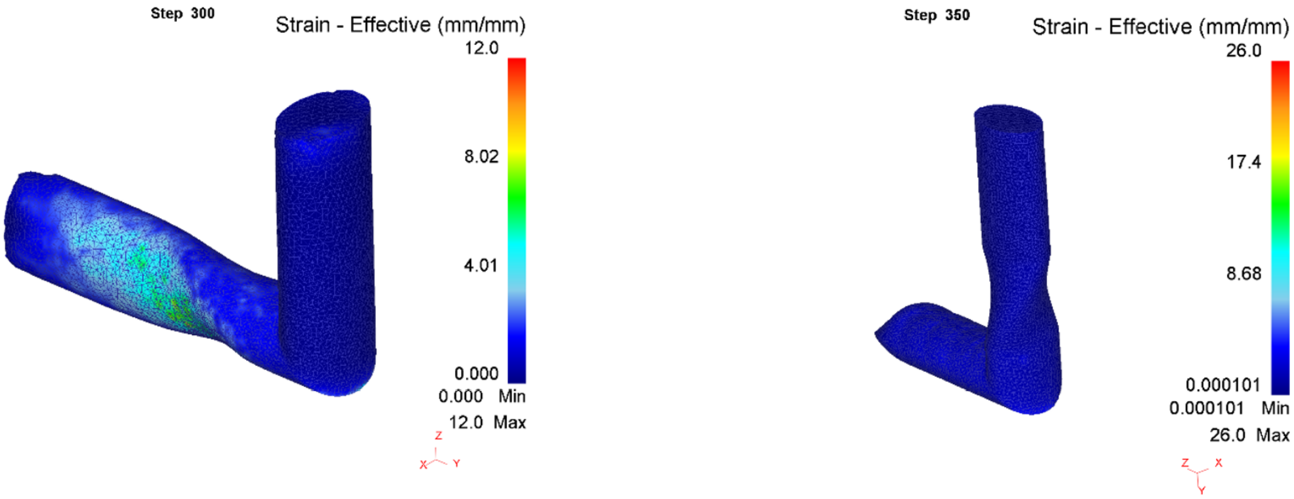
$$\varepsilon_{0.5} = a_5 d_0^{h5} \varepsilon^{n5} \dot{\varepsilon}^{m5} \exp\left(\frac{Q_5}{RT}\right) + C_5 \tag{7}$$

$$d_{DRX} = a_8 d_0^{h8} \varepsilon^{n8} \dot{\varepsilon}^{m8} \exp\left(\frac{Q_8}{RT}\right) + C_8 \tag{8}$$

In these equations, X_{DRX} represents the volume fraction of recrystallization and β_d of Avrami constant, and d_0 is the initial grain size. As mentioned above, according to the material and type of simulation in the flow stress analysis, the Arrhenius equation is used according to Eq. (2). In this equation the value of A is 5.83×10^{18}, and activation energy is 2.6406×10^5, α is 0.012, and n is 39 for Aluminum alloy 7050. Furthermore, constant values are provided in Table 1. Also, to investigate the microstructure of the material, the average and initial grain sizes are considered 100 microns.

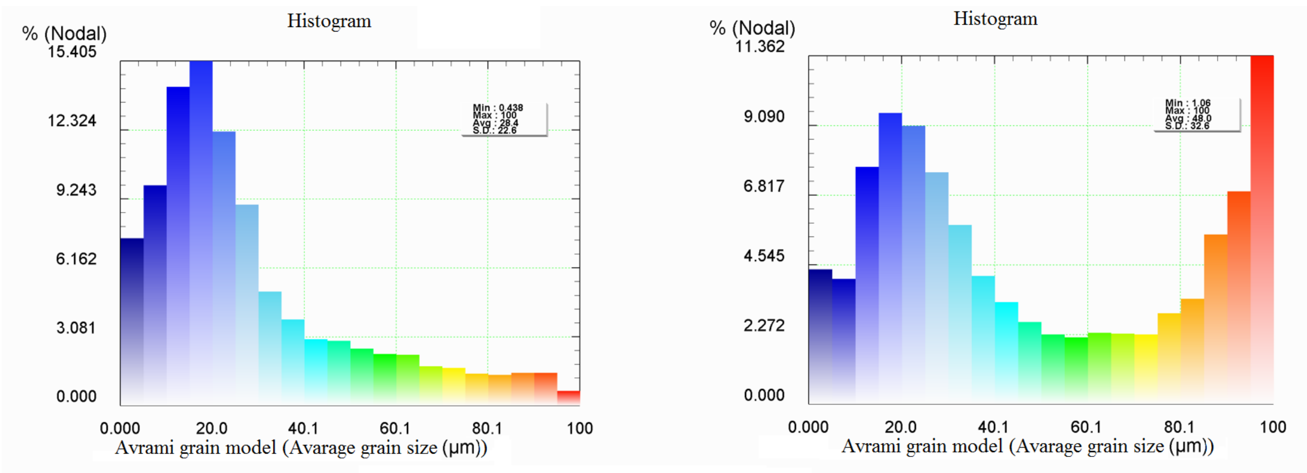
Table 1
Constant values of dynamic recrystallization equations related to Al alloy 75050 [20].

β_d	K_d	Q_5	Q_8	a_5	a_8	a_{10}	h_5	m_5	m_8
0.693	2	53350	-19002.72	0.0000121	78.6022	0.8	0.13	0.04	-0.03722



a b

Fig. 3. Strain distribution of billet which is deformed by a) ECAP+TE and b) TE+ECAP.



a **b**

Fig. 4. Average grain size histogram in both modes a) ECAP+TE b) TE+ECAP.

3. Results

3.1. Investigation of the Effect of Twist Area Location

Fig. 3 presents two modes regarding the place of the twist channel in the TCAP process. Also, the results of these two modes on the size of the billet grain and the punch force for forming in Figs. 4 and 5 can be observed respectively. The initial average grain size in both cases is 100 microns.

As obtained from histograms in Fig. 4 and Table 2, the grain size is smaller when the twist section is located after the ECAP section. By considering the standard deviations and average grain sizes in two conditions, it can be said that locating the twist section after the ECAP channel improves the microstructure. In ECAP+TE mode, the Average strain applied to the billet is about 2.23 and in TE+ECAP is about 1.95. However, the standard deviation of strain in the second state is 0.05 less than the first one. The strain homogeneity of the two cases are close, although the b state is slightly more homogeneous due to the presence of the ECAP region after the twist channel. The values of standard deviations of both states are given in Table 2. The strain distributions of both states can be seen in Fig. 3. So, Small grain size in ECAP+TE mode is due to the amount and homogeneity of strain applied to the billet and also the temperature of the billet during the process. In addition, the temperature of the billet increased from 250°C to 289°C at the end of the process, but in the second case, the temperature increased to 297°C. Therefore, the billet becomes fine grain during the first process. In Table 2, the values related to the average grain size and its standard deviation for both cases are listed. Another parameter that is considered in the design of dies and processes is the punch force for forming. In Fig. 5, the force-displacement diagrams of both modes are shown.

In Fig. 5, the placement of the twist channel after the ECAP channel made an increase in force. By locating the twist channel after the ECAP channel, the required punch force for the process has been increased from 66.1KN to 66.3KN. According to the above-mentioned figures and explanations, it can be concluded that placing the twist channel after the ECAP channel in the form of Twist Channel Angular Pressing (TCAP) process improves the microstructure of the material, increases the imposed strain while the homogeneity of strain is stable after the process, and also doesn't affect the force of process considerably. Therefore, according to the analysis, for the simulations that follow the twist section is located after the ECAP channel.

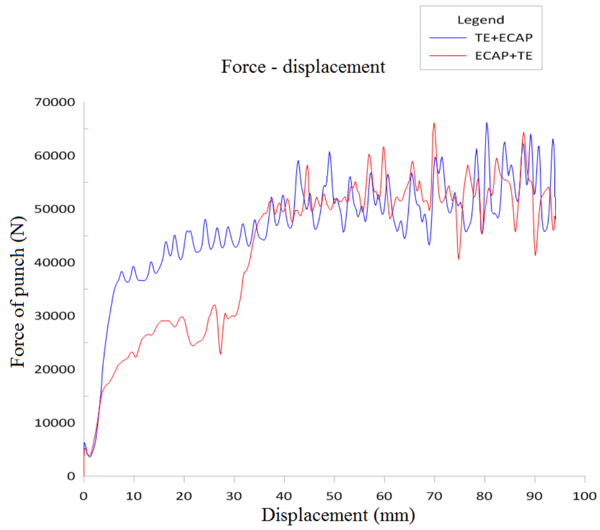


Fig. 5. Corresponding force-displacement diagram for two extruded samples.

3.2. Plastic Strain Distribution

In Fig. 6, contours and the strain distribution of equivalent plastic strain and related histogram at a section with a distance of 20mm from the forehead of the billet is shown in the sample with an ECAP angle of 110°, and a twist angle of 45°. In Table 3, numerical values related to plastic equivalent strain for all cases are mentioned in the cutoff section.

Table 2
Average grain size and standard deviation of both stated modes.

Die type	Standard deviation (Average strain)	Average strain	Standard deviation (Average grain size)	Average grain size
ECAP+TE	1.23	2.23	22.6	28.4
TE+ECAP	1.18	1.95	32.6	48

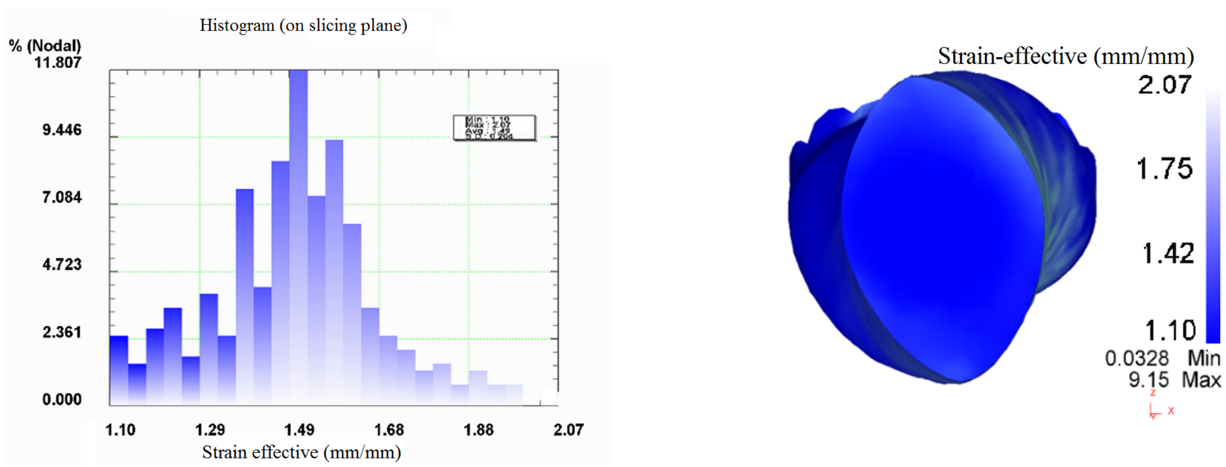


Fig. 6. The corresponding strain and histogram distribution of the extruded sample under elliptical cross-section with an internal angle of 110°, a corner angle of 0° and a twist angle of 45°.

Table 3
Statistical values related to the strain of different cases.

External corner angle (°)	ECAP internal angle (°)	Twist angle (°)	Standard deviation	Average strain value	Minimum strain value	Maximum strain value
0			0.541	1.99	1.44	3.90
10	90		0.259	1.71	1.24	2.00
20			0.164	1.59	1.24	1.98
0			0.412	1.81	1.30	3.69
10	100	30	0.362	1.66	1.21	2.45
20			0.379	1.26	0.0240	4.75
0			0.436	1.29	0.984	1.66
10	110		0.0970	1.17	0.982	1.42
20			0.273	1.13	0.941	1.47
0			0.483	2.01	1.46	4.19
10	90		0.258	1.99	1.42	2.68
20			0.297	1.95	1.50	2.89
0			0.312	1.95	1.59	3.20
10	100	45	0.183	1.53	1.10	1.68
20			0.188	1.37	1.27	2.15
0			0.204	1.49	1.10	2.07
10	110		0.176	1.30	0.0432	7.42
20			0.184	1.26	1.09	1.95
0			0.414	2.37	1.48	3.96
10	90		0.658	2.36	1.65	3.27
20			0.499	2.33	1.62	3.96
0			0.709	2.33	1.47	4.67
10	100	60	0.486	2.13	1.35	3.22
20			0.702	1.96	0.0615	4.3
0			0.486	2.29	1.76	3.85
10	110		0.568	2.15	1.35	4.02
20			0.456	1.94	1.15	2.85

As it is shown in Fig. 6, the strain distribution of plastic equivalent from the center to the outer points increases slightly. This causes heterogeneity in microstructure and brings about changes in the mechanical strength of the produced material. This has also been observed in the research of Heydari et al. [17]. One of the factors that affect this heterogeneity is friction coefficient, the geometry of the sample cross-section, and geometric characteristics of the die including, twist angle, internal angle, etc. The reduction of this heterogeneity is an interesting issue for researchers and one of the characteristics of the proper deformation process to achieve good plastic strain with low standard deviation. As can be seen in Table 3, by increasing the twist angle, the amount of plastic strain has increased in almost all cases. Also, the 45° twist angle has resulted in the best strain homogeneity, similar to the research of Mohammad Iqbal et al. [18]. On the other hand, the increase of internal angle and the corner angle have helped deformed billet to flow in the die smoother, and as a result, the average strain has decreased. By increasing the internal angle, an increase in the strain homogeneity of the sample according to the standard deviations is not observed in some cases. However, increasing of homogeneity has been followed by increasing the internal angle in Mohammad Iqbal et al.'s paper [18] for all cases with rectangular cross-sections. The homogeneity of the effective strain from this change in the internal angle on the billet can be due to the reduction of the dead zone of the material. This difference between the results can be related to the change in the geometry of the die cross-section and the substitution of the two channels of twisting and bending. Another visible effect is the effect of corner angle on the average strain with increasing internal angle. It is reported from the ECAP study of Agwa et al.'s paper [12] that the effect of corner angle on strain is decreased by increasing the internal angle, indicating that the corner angle only affects the dies with slight and sharp internal angle. In this research, for example, it can be stated that at the twist angle of 30° and the internal angle of 90°, the increase in the corner angle completely reduces the average strain. This effect has been reduced by increasing the internal angle at the twist angle of 30°, which is similar to the results of the research of Agwa et al. [12] However, due to the existence of a twist channel in the TCAP process, changing the corner angle by increasing the internal angle leads to fluctuations in the average strain of some samples with other twist angles. However, it should also be noted that adding the twist channel (TE) to the ECAP channel has improved the effect of corner angle changes on strain well in all different angles of the channel, unlike those obtained in the research of Agwa et al. [12]. From 0° to 10° at a twist angle of 30°and an internal angle of 90°, a decrease of 0.28 and a twist angle of 45° and an internal angle of 100° a reduction of 0.42 in the average strain are observed.

3.3. Microstructure

In Fig. 7, contours and grain size distribution with related histogram at a cross-section with a distance of 20mm from the forehead of an extruded sample with an internal angle of 110° and a twist angle of 45° are shown. Also, in Table 4, the values related to the microstructure of samples are listed in all cases. Looking at Fig. 6, it can be observed that the strains in the center of the billet are less than other areas of the billet, so that the size of the grains in the center of the sample cross-section is more significant than outside of the center of the cross-section. On the corners of the billet and the outside areas, due to more strain, the grain size is much smaller than the center of the billet.

As Table 4 shows at the constant twist and corner angles, increasing the internal angle leads to larger standard deviation values and more heterogeneity of the material's microstructure. Since homogeneity and fine grain size are also important factors in improving mechanical properties, this heterogeneity can lead to weakness in the microstructure. In Fig. 8, the variations of the strain and average grain size are shown on a diagonal line from the cross-section. As it is noted in this paper, the moderate strain variations have caused changes in grain size.

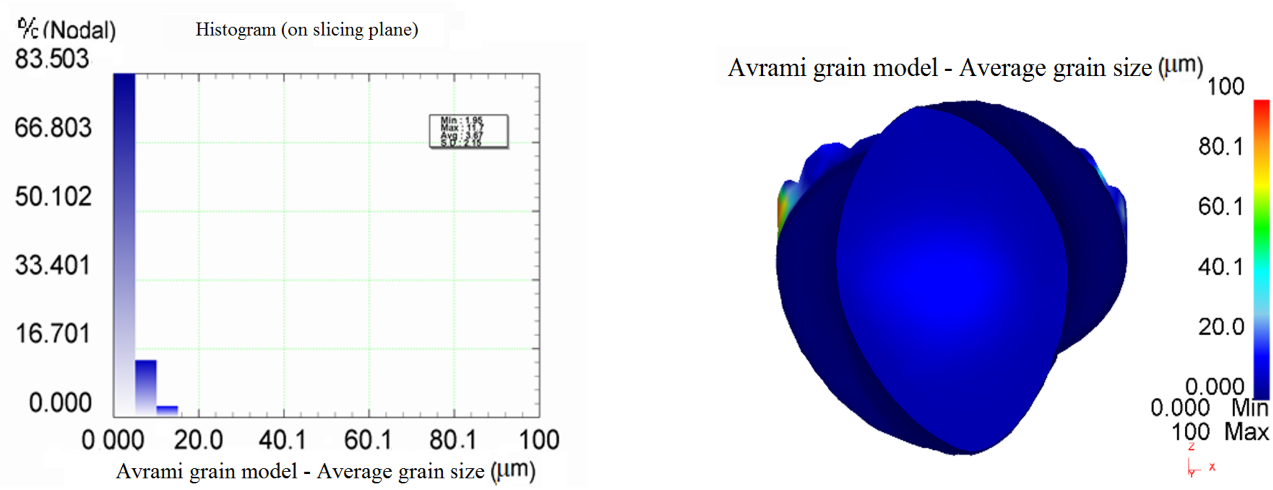


Fig. 7. Grain size distribution and corresponding histogram for the extruded sample with 110° internal angle, 0° corner angle, and 45° twist angle.

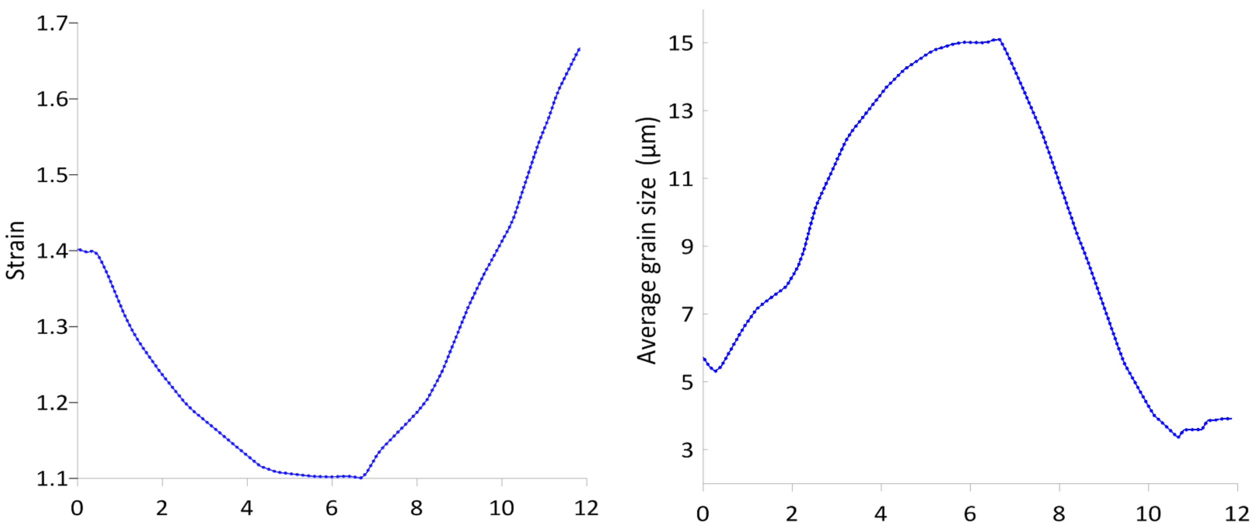


Fig. 8. Diagram of variations of a) Strain b) Average grain size on a diagonal line.

Table 4
Statistical values related to the microstructure of different cases.

External corner angle (°)	ECAP internal angle (°)	Twist angle (°)	Standard deviation	Average grain size (μm)	Minimum grain size (μm)	Maximum grain size (μm)
0			3.36	14.90	9.94	24.60
10	90		3.40	10.70	6.61	25.70
20			3.08	12.90	7.73	24.00
0			3.66	13.50	7.64	22.50
10	100	30	3.99	12.00	2.05	17.10
20			6.16	19.50	3.97	29.50
0			6.59	24.50	7.76	40.60
10	110		5.38	32.50	12.55	44.20
20			8.23	45.40	16.10	45.70
0			4.93	13.77	8.31	37.40
10	90		1.82	10.40	6.04	15.10
20			2.76	11.30	7.66	20.40
0			1.52	12.80	12.20	19.70
10	100	45	3.63	5.63	2.90	15.20
20			3.74	6.36	2.23	20.90
0			2.15	3.67	1.95	11.70
10	110		5.64	14.70	12.20	38.50
20			5.49	14.50	4.58	28.80
0			4.07	11.10	4.52	22.10
10	90		1.85	17.70	12.9	22.80
20			7.28	16.10	5.58	43.00
0			5.45	16.20	10.30	39.90
10	100	60	3.50	12.50	3.64	19.90
20			3.06	17.50	2.83	18.20
0			1.83	16.50	8.76	20.60
10	110		2.42	15.30	10.70	25.50
20			3.43	15.90	2.87	20.20

This effect i.e., increasing the internal angle, which is also discussed in a paper on the ECAP process conducted by Naik et al. [7], has made a weakness in the microstructure. However, it can be said that increase in internal angle in the case of using the combined TCAP die, although it is led to an increase in heterogeneity of the microstructure in some cases. Still, due to the presence of the twisting angle effect and the compound effect caused by bending and twisting, this weakness in the microstructure of the material is somewhat compensated compared to the ECAP process. In addition, according to the results, to create more homogeneity in the microstructure of the material in the case of using 90° and 100° internal angles in the TCAP die, the use of 45° twist angle helps. In contrast, the 60° twist angle creates more homogeneity in the microstructure billet if using the 110° internal angle. In addition, by observing Table 3 with Fig. 6, the discussion of strain and its homogeneity as effective factors on the microstructure is also concluded. By comparing the strain values and grain size, it is supposed that the low standard deviation along with the appropriate imposed strain is very effective in grain size and its distribution. Based on obtained results for ECAP+TE, it can be said that if the average strain applied to the billet is more than 1.35 and the standard deviation is about 0.3 at most, a relatively fine grain size (below 11 micrometers) will be obtained in the material. If each of these effective parameters change, it leads to changes in the size of the grain size. In TE papers such as Heydari et al. [17], the grain size of the material has become smaller by increasing the twist angle, while by adding the ECAP channel to the TE process, this improvement process has changed somewhat. Increasing the twist angle in the TCAP process does not wholly and definitively improve the material's microstructure. Besides, to understand the trend of temperature changes in the billet during deformation, the diagram of temperature changes for the same element that deformed in TCAP dies with different twist angles is shown in Fig. 9. As shown in Fig. 9, the sections with the highest temperature are different for each die due to the various temperature decrease and increase trends. Based on Fig. 9 more uniform temperature changing can be seen in billets which are deformed by dies with twist angles of 45° and 30°, especially the die with twist angle of 45°, than the billet which is deformed by die with twist angle of 60°. Therefore, in designing these types of dies, all factors should be considered together, and finally, the optimal dimensions should be extracted.

The critical point about this research is the average grain size in the best dimensions of the die (twist angle 45°, internal angle 110°, and corner angle 0°); in this case, the average grain size is 3.67μm. If compared with Heydari et al.'s [17] research, it can be observed that in the best dimensions of die related to twist extrusion process (TE), the average grain size has reached approximately 6.5μm and therefore, the TCAP process has been able to reduce the average grain size about 44% compared to TE process. In small grain sizes, the accumulation of dislocations prevents the creation of finer microstructure, which the TCAP die has been able to overcome to some extent.

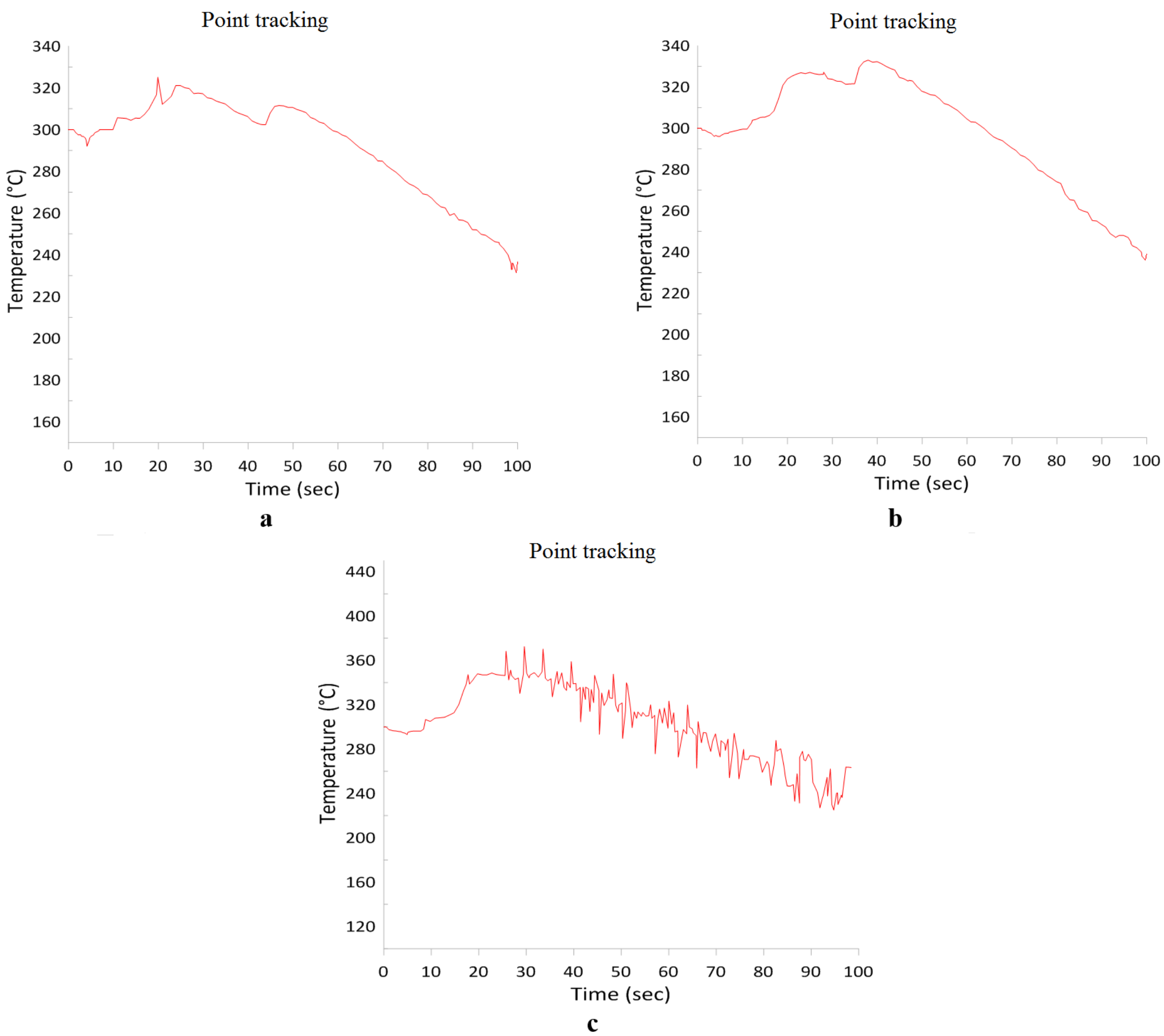


Fig. 9. Temperature changes of a point in the center of the forehead of the die billets with an internal angle of 110°, corner angle 10° and twist angle a) 30° b) 45° c) 60°.

Table 5
Coded simulation modes.

90-30-0	90-30-10	90-30-20	90-45-0	90-45-10	90-45-20	90-60-0	90-60-10	90-60-20
A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9
100-30-0	100-30-10	100-30-20	100-45-0	100-45-10	100-45-20	100-60-0	100-60-10	100-60-20
B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9
110-30-0	110-30-10	110-30-20	110-45-0	110-45-10	110-45-20	110-60-0	110-60-10	110-60-20
C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9

3.4. Force

The required punch force for forming of materials is one of the factors that has a significant influence on the process and cost of forming operations. In Fig. 10, the maximum force values required to perform the process are shown in different modes. Different simulation cases are coded in Table 5 for ease of graph representation.

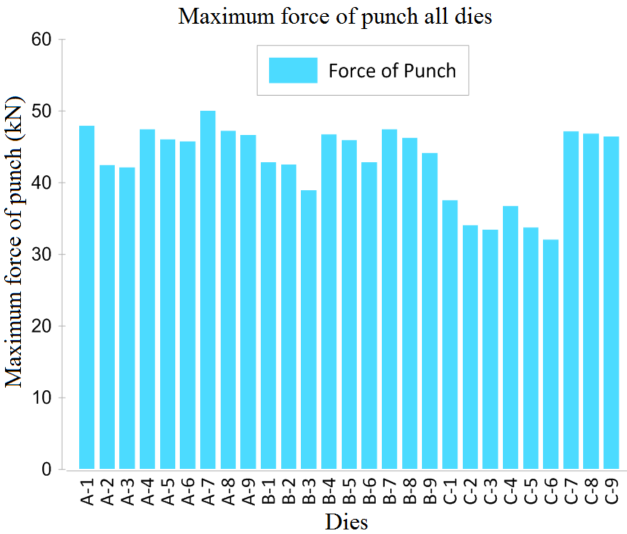


Fig. 10. Maximum punch force diagram in all cases in KN.

From the observation of Fig. 10, it can be found that in most cases, by increasing the twist angle to 60°, unlike previous research with rectangular cross-section [21], there is an increase in punch force. This difference in changing the punch force can be caused by locating the twist section after the ECAP section. Also, by increasing the internal angle and corner angle, in most cases, the reduction of punch force is achieved. In other words, increasing the angle of the corner helps to make the flow of matter fluent during the deformation. Also in the lowest force state, it can be said that this value is equal to 32.1KN. This amount occurs at a twist angle of 30° and a corner angle of 20°, and an internal angle of 110°. The maximum force value also occurs at a twist angle of 60° and a corner angle of 0°, and an internal angle of 90°. As shown in Fig. 10, the samples with an internal angle of 110° and a twist angle from 30° to 45°have the lowest required force for forming.

4. Conclusions

In this paper, the effect of geometric parameters of TCAP die on strain distribution of plastic, microstructure, and required punch force for forming aluminum alloy 7050 with the initial and average grain size of 100μm is investigated using simulation in DEFORM 3D software. The most important results of this study are as follows:

1. Placement of TE channel after ECAP channel reduces the required punch force for forming and decreases the average grain size of the sample.

2. Increasing the twist angle of the die helps to increase the average strain which is imposed to the billet.

3. TCAP die can reduce the average grain size from 100μm to about 3μpm if die dimensions are optimally selected.

4. By selecting elliptical cross-section, 110° internal angle, 0° corner angle, and 45° twist angle are optimal geometric parameters of TCAP die.

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