На основі комп'ютерного 3D-моделювання виконано дослідження впливу коефіцієнта тертя на деформацію та її розподіл для зразків з алюмінієвого сплаву 5052. Ефект тертя був досліджений за трьома рівнями варіації коефіцієнтів тертя (0:01; 0:025; 0:05). Результати дозволили зробити висновки щодо характеру розподілу та чисельних значень деформації та мікротвердості для різних коефіцієнтів тертя

Ключові слова: штамп, алюміній, ECAP, тертя, мікротвердість, деформація

На основе компьютерного 3D-моделирования исследовано влияние коэффициента трения на деформацию и ее распределение для образцов из алюминиевого сплава 5052. Эффект трения был исследован для трёх уровней вариации коэффициентов трения (0:01; 0025; 0:05). Результаты позволили сделать выводы о характере распределения и численных значениях деформации и микротвердости для различных коэффициентов трения

Ключевые слова: штамп, алюминий, ECAP, трение, микротвердость, деформация

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THE ANALYSIS OF FRICTION EFFECT ON EQUAL CHANNEL ANGULAR PRESSING (ECAP) PROCESS ON ALUMINIUM 5052 TO HOMOGENEITY OF STRAIN DISTRIBUTION

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1. Introduction

ECAP (Equal Channel Angular Pressing) is an innovative process to obtain severe plastic deformation (SPD) and superior mechanical properties through grain refining technique [1]. UFG (Ultra-fine Grained) material is a material with granules between 10 nm to 100 nm. The ECAP processes can be performed on several materials, both single crystals, polycrystalline [2] and metal-matrix composites [1]. Aluminum and its alloys are popular materials used in the ECAP process.

Experimental ECAP process studies had been developed by varying important process parameters such as intersection angle, fillet radius and friction factor [3, 4]. Optimal die design and homogenous distribution of shear stress are the objectives of the ECAP process product. The inhomogeneous deformation measured using the deformation inhomogeneity index (I) based on the width of the billet was found to increase gradually with increasing shear friction value [5]. Modeling from the previous study resulted in dies with specific parameters, the effect of friction on the dies has not been further investigated. On the other hand, computer simulations evolved as a favorite tool to predict process parameters to obtain optimal dies design. By using computer simulation, initial prediction of process parameters and dies design can be constructed to reduce the experimental trial and errors, and cost and time of production process can be minimized. In the previous study, the computer simulation on the ECAP process was investigated by using a 2-dimensional model with the plane strain assumption [6]. The advantage of the 2D simulation is very fast completion of running, but the results obtained can be presented only two-dimensional. Three-dimensional modeling to determine the effect of friction between the billet with the entire surface of dies was performed. Friction will affect the strain on the billet thus affecting the strain homogeneity of the billet. In this study, the ECAP process is simulated in 3 dimensions to provide more information on the analysis of ECAP process results.

2. Literature review and problem statement

Grain size refinement is one of the methods to improve mechanical properties of metals (aluminium). Equal channel angular pressing (ECAP) is one of the severe plastic deformation techniques, which can produce very small grains in materials [7], even can reach ultrafine to nanoscale grains [8]. In the ECAP process, the billet is pressed through a die, which has two channels of an equal cross section and the channel has a certain angle [9].

Strain distribution in the ECAP process is affected by various parameters such as corner angle [10], back pressure [11], strain hardening rate, inner corner angle, processing route [12], friction [5]. Luri et. al. studied the effect of the inner corner angle and outer corner angle on strain distribution in the ECAP process[13].

Various parameters in the ECAP process can be divided into two categories: 1. Dies parameter and 2. Process parameter. Modelling on dies parameter in the previous research obtained new dies design, the dies parameters are channel angle of 105°, inner fillet radius of 0 mm, outer fillet radius of 5 mm [6]. This dies parameter resulted from 2D modelling.

The 3D simulation performed by Patil is done on a die that has a round shape instead of a square. While research by Djavanroodi [14] investigated the channel angle effect, buckle and back pressure at dies with a tubular cross-section. Similarly, the research conducted by Mahallawy [15] on the homogeneity of plastic deformation is also done on a tubular die. The homogeneous research on the ECAP process with the dies geometry generated from the previous studies in 3D has not been studied in more detail.

In the ECAP process with dies, the frictional tubes are more complex, compared to friction that occurs in prints that have square sections [16].

3. The aim and objectives of the study

The aim of the research is to predict the effect of friction on the strain distribution on aluminum on cross section after the Equal Channel Angular Pressing process with 3D simulation. The strain distribution is verified with microhardness test.

To achieve this aim, the following tasks are identified:

1. 3D modelling of the ECAP Process with various friction values using the Finite Element Software.
2. Calculation of the strain homogeneity of aluminium based on ECAP process modeling.
3. Microhardness testing on the cross section of aluminium after processed with ECAP.

4. Materials and methods of research

It is difficult to directly measure strain and its distribution in the billet material during the ECAP process. However, the deformation, strain distribution and stress state in the billet material during the ECAP process can be estimated by computer simulation based on FEM. In the previous study [7], the 2D model of ECAP had been developed. The 2D model was chosen due to the simplicity of CAD and faster running time. Unfortunately, the 2D model provides limited information on metal flow and strain distribution only in plane-view. The 3D model is utilized due to the requirement of strain distribution observation on different zones and gives a clear idea of metal flow. Therefore, the application software based on Finite Element Analysis was employed for the ECAP process simulations. The three-dimensional model was constructed. The die was modeled as a rigid body, and the billet material was assumed as an elastic-plastic model. The effect of friction was investigated, respectively, with 0.01; 0.025 and 0.05 friction coefficients. The dimension of rectangular billet material is 10×10 mm. Meshing is adopted with fine condition and element size is set to 0.1 mm (total mesh 4000/10×10×40) (Fig. 1). ECAP (Equal Channel Angular Pressing) is an innovative process to obtain severe plastic deformation (SPD) and superior mechanical properties through grain refining.

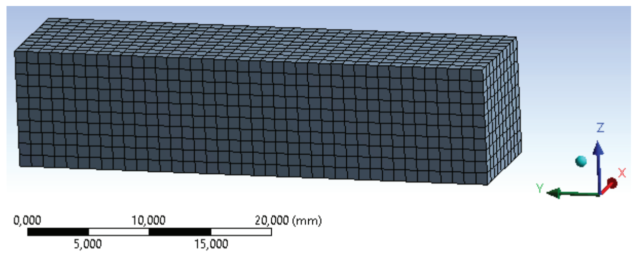


Fig. 1. Aluminium billet meshing

Material model was assumed as a bilinear isotropic hardening model. The geometry of dies is based on previous experimental geometry [6] with a channel angle of 105°, inner fillet radius of 0 mm, and outer fillet radius of 5 mm (Fig. 2). Strain distribution is observed through the center of the die and billet. The ECAP simulation result was verified by using experimental data. Fig. 3 shows the model of the ECAP process.

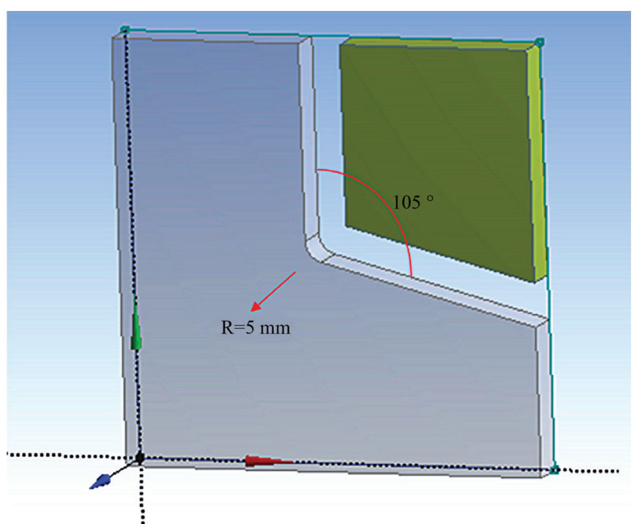


Fig. 2. ECAP dies parameter

Aluminium hardness in cross section was tested by using a microhardness tester; hardness testing was used to support the analysis of strain distribution from modeling. The aluminium billet was cut on the middle section of the billet. The size of the test specimen for microhardness testing is adjusted to the capacity of the microhardness-testing machine. The sample was mounted with epoxy resin for easier in the additional process. Additionally, the sample was sand with sand paper from grit 100, 200, 500 and 1,000, respectively. The microhardness test position is shown in Fig. 3, the billet cut on the middle position.

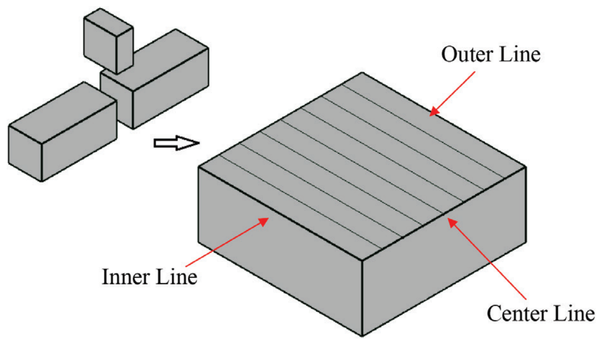


Fig. 3. Microhardness testing position

The microhardness testing position on the line (Fig. 3).

5. Experimental data and processing of the obtained results of experiment

The result of modeling the ECAP process can be shown in Fig. 4. At the initial stages, larger strains occur in the upper part of the billet material as shown in Fig. 4. At the subsequent stages, these parts flow slower than the material at the bottom part as a consequence of the flow material rule. This variation of the strain distribution in the cross-section of the exit channel produces the formation of a corner gap. This condition is related to the lower shear strains at the bottom part of the pressed billet material. The blue color of the billet indicates the lowest strain (0) and red indicates the highest strain (0.83 mm/mm). The red value depends on the friction, of Fig. 5 was for modeling with friction 0.025.

The corner gap in the ECAP process can be shown in Fig. 6; the biggest corner gap occurs in the ECAP process with a friction coefficient of 0.01, while the ECAP process with a friction coefficient of 0.05 the corner gap does not occur. The corner gap in this ECAP process occurs due to friction between the billet and the dies.

The examples of deformed shapes of billet material according to different friction are shown in Fig. 6, *a* – 0.01, Fig. 6, *b* – 0.025 and Fig. 6, *c* – 0.5). This ECAP dies is developed uses the channel angle of 105° to reduce the corner gap of the final ECAP product. However, based on deformed shape, the corner gap still appears in 0.01 friction condition.

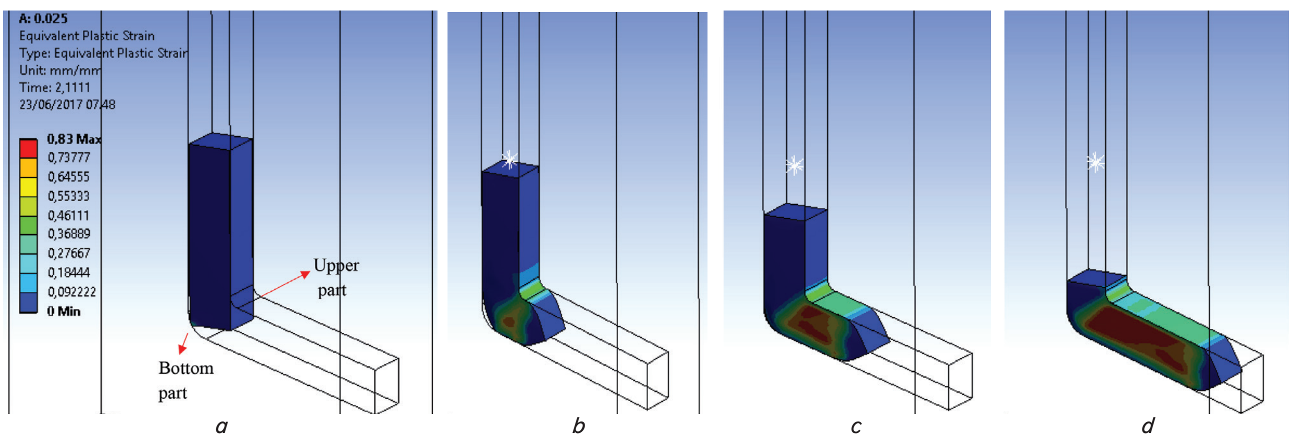


Fig. 4 Mechanism of metal flow during the ECAP process based on strain distribution plot:
a — initial stage; *b* — billet start to enter channel angle, *c* — upper side of billet; *d* — final stage

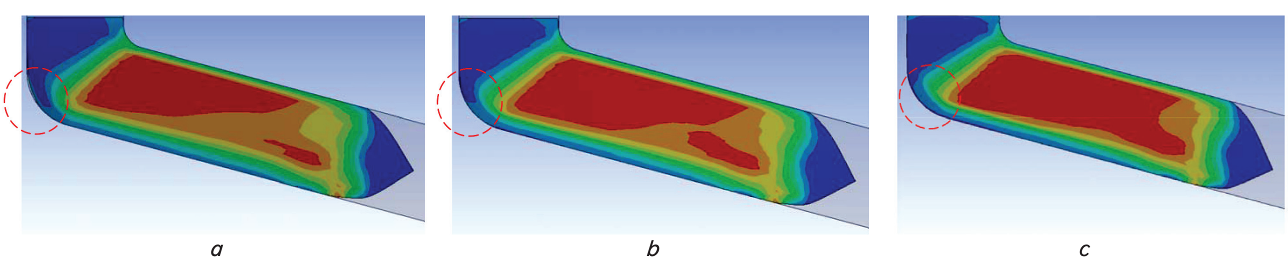


Fig. 5. Plot of corner gap and strain distribution on the billet with various friction values: *a* — 0.01; *b* — 0.02; *c* — 0.05

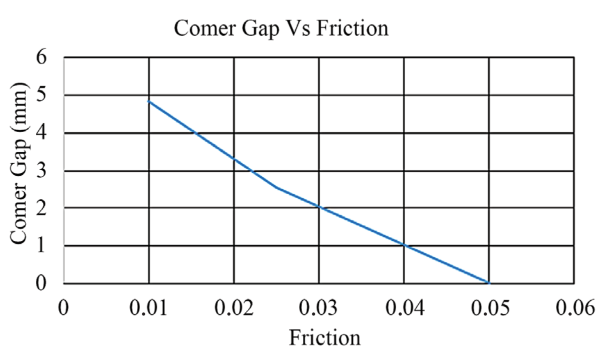


Fig. 6. Effect of friction on the corner gap in the ECAP process

The corner gap is smaller in 0.025 and 0.05 friction condition. This phenomenon is a similar trend with the previous study, in which friction increases as the corner gap decreases. The plastic deformation zone is wide for 0.01 friction condition, and as the friction increases, it becomes narrow. This condition is explained as a back pressure leading to the filling of the corner gap. The strain distribution showed that 0.05 friction produces more uniform strain than 0.025 and 0.01 friction.

The reaction force during the ECAP process can be shown in Fig. 7.

The reaction force data are gathered from the modelling result, these data can be shown in report preview. The simulation was performed using the Ansys FA package software. In this software, the reaction force is time vs reaction, we convert the time into displacement.

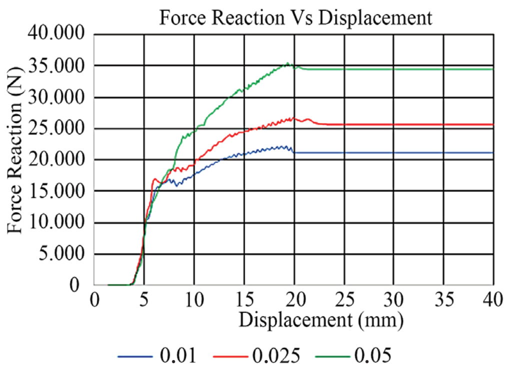


Fig. 7. Strain-stress during the ECAP process

The push backward of the billet increased the strain on the billet, the increase of strain can be shown in Fig. 8.

The lowest strain occurs in the ECAP process with friction 0.01, next 0.025 and the highest 0.05. The increase of strain due to the lowest corner gap makes a lower angle; it makes the highest strain to occurs [17].

The increase of strain is due to the coefficient of friction, friction also influences strain homogeneity.

The degree of strain inhomogeneity can be estimated using the equations proposed [10]. Which is given by Equations (1), respectively.

$$Ci = \frac{\mathrm{Max}_{eps} - \mathrm{Min}_{eps}}{\mathrm{Avg}_{eps}}, \quad (1)$$

where Ci – strain inhomogeneity index; Min_{eps} – minimum equivalent plastic strain; Max_{eps} – maximum equivalent plastic strain; Min_{eps} – minimum equivalent plastic strain; Avg_{eps} – average equivalent plastic strain.

The strain value distribution can be shown in Fig. 9, 10.

The maximum strain on aluminium after the ECAP process is shown in Fig. 10, the highest strain occurs in the ECAP process with the coefficient of friction of 0.05.

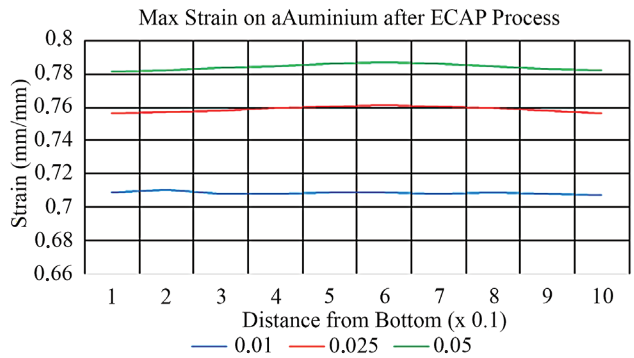
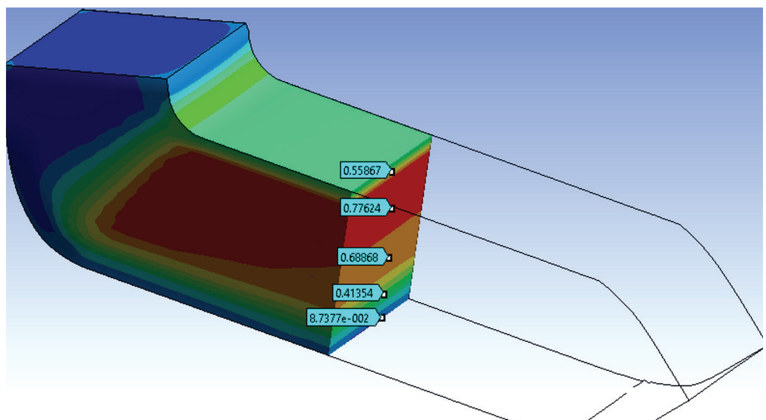
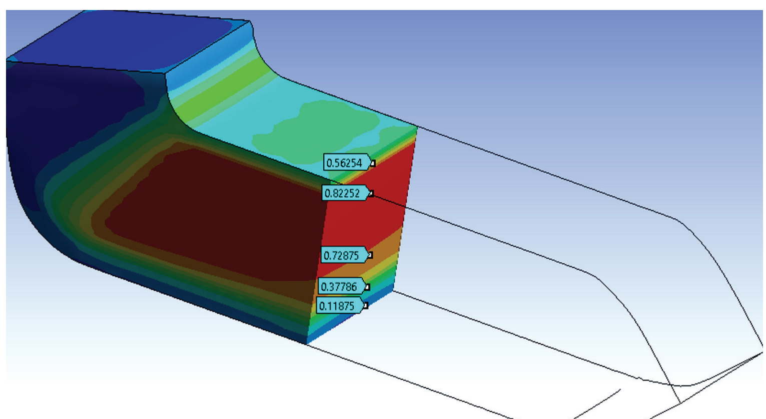


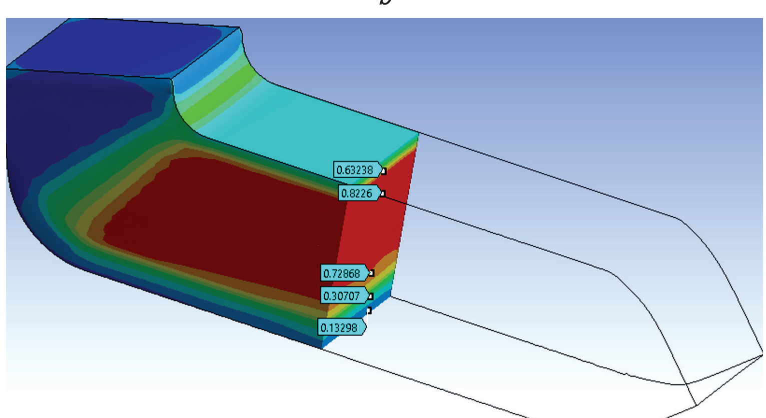
Fig. 8. Strain on the billet center line



a



b



c

Fig. 9. Plot of strain distribution on a slice cross section of the billet with various friction values: *a* – 0.01; *b* – 0.025; *c* – 0.05

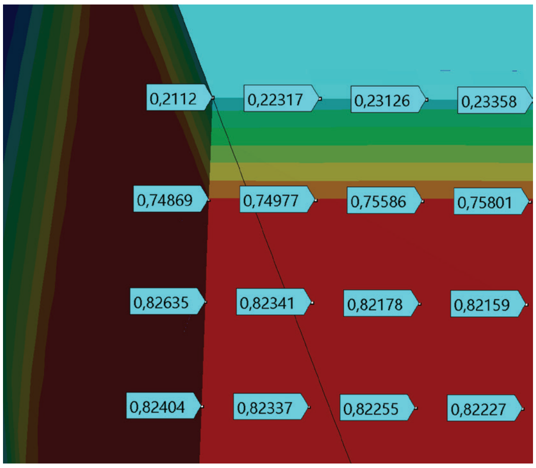


Fig. 10. Strain value on the friction value of 0.05

The strain inhomogeneity index and the coefficient of variance of equivalent plastic strain estimated are shown in Fig. 11. A lower value of the index indicates better homogeneity. It can be noted that 0.05 friction has better homogeneity. This decision is supported that 0.05 friction produces a smaller corner gap and more uniform strain as shown in Fig. 5.

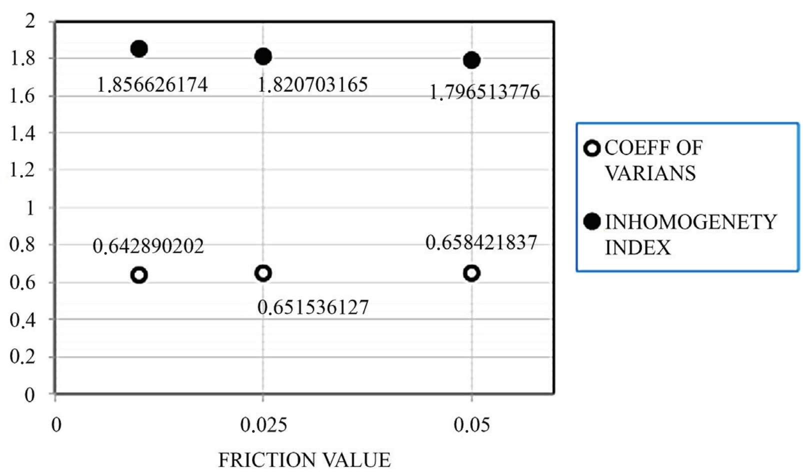


Fig. 11. Inhomogeneity index (Ci) and coefficient of variance of equivalent plastic strain on friction value variation

Microhardness.

Microhardness testing on a cross-section of aluminium after the ECAP process is shown in Fig. 12.

Aluminum hardness in cross-section shows that the highest hardness occurs in the centerline of the billet, while the outer part (1 mm from the edge) has a higher hardness than the inner line.

The hardness distribution on aluminium complies to strain distribution on ECAP modeling. The highest hardness occurs in the center line of the billet. While the lowest occurs inside the billet. Hardness distribution on the center line depends on the distance to edge, the hardness on the edge is higher than in the center. This is due to friction between the billet and dies. It happens outside and inside of the billet. This hardness distribution is related to the strain distribution, it can be observed that increasing strain produces higher hardness [18].

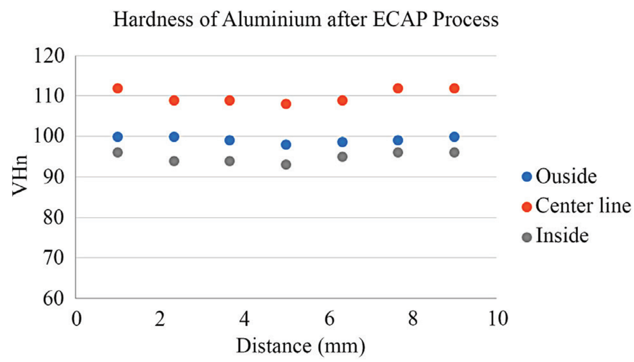


Fig. 12. Hardness of aluminium after the ECAP process

6. Discussion

The ECAP process using 0.05 friction resulted from the most homogeneous strain. This can be seen from the corner gap that occurs, according to the smaller corner gap, the more homogeneous strain that occurs. This can be proved by homogeneity calculation. The homogeneity index is determined by measuring the strain that occurs on the workpiece in the ECAP process. Measurement of strain in the ECAP process cannot be done because it is too difficult to measure strain at each position of the workpiece, besides the size of the workpiece, the distance between the measurement points is very close and installation of the strain gauge to measure the strain cannot be done. In addition, in the ECAP workpiece, the strain gauge cannot be installed, the sensor (strain gauge) will be damaged when the ECAP process is done.

Increasing friction coefficient is affected by stress on the workpiece, the increase of stress on the workpiece reduced the corner gap between dies and billet, event in ECAP with a coefficient of friction of 0.05 the corner gap between the billet and dies does not occur.

In addition, the reducing size of the corner gap also increases force reaction in the ECAP process (Fig. 7). The higher friction coefficient resulted from the higher force reaction. The increase of reaction force leads to strain on the workpiece (Fig. 9), so it will increase the hardness of aluminium (Fig. 12).

The most homogeneous strains in the ECAP process occur in the ECAP process with 0.05 friction. This can be confirmed by homogeneity index calculation. The smaller the homogeneous index, the more homogeneous strain that occurs. The result of this calculation is confirmed by microhardness test, microhardness pattern on the workpiece cutting piece according to the modelling result.

6. Conclusions

1. The 3D ECAP process modeling demonstrates the ECAP process with the 0.05 friction coefficient tidak menghasilkan corner gap, pada modelling dengan koefisen gesek 0, 0.025 corner gap yang terjadi adalah 2.6 mm and at friction 0.01 the corner gap 4.9 mm. Its corner gap indicates the strain homogeneities.

2. Calculations of homogeneities by two methods show that the ECAP process with 0.05 friction results in the most homogeneous strain.

3. The microhardness measurement on the cross section of aluminum after ECAP shows a similar pattern to the strain occurring in aluminum after the ECAP process.

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