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Research Paper

Study of Mechanical Properties of 7075 Aluminum Alloy Due to Particle Size Reduction due to Constrained Groove Pressing CGP Process

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Abstract
Today, one of the new approaches of researchers to produce materials with very fine grains is the application of severe plastic deformation on the prototype with coarse grains. In this method, the grain size is reduced to the nanometer scale in several stages through applying strong strains to the sample, which leads to the improvement of mechanical and physical properties in the material. One of the most important methods of applying severe plastic deformation is the constrained groove pressing (CGP) process. According to studies, little research has been done on the weight loss of structures used in the military, maritime, aviation, and medical industries. Therefore, the mechanical behavior of the sheets was experimentally studied by the CGP method. The results show that the structure of 7075-T6 aluminum particles decreased in size from 60 microns to 270 nanometers by increasing the steps of this process. Also, the yield strength in the fourth pass increased by 38% compared to the annealed sample, and the tensile strength improved by 34%. In addition, the percentage of longitudinal increases in the fourth pass is reduced to its lowest value, ie 40%.

Keywords
Constrained Groove Pressing Process, 7075 Aluminum Alloy, Ultrafine-grained Materials, Mechanical properties

1. Introduction
Structures made by several plastic deformation methods have very good physical and mechanical properties due to their unique internal structure. These unique properties make ultrafine-grained (UFG) materials suitable for many commercial applications. Therefore, as the size of the grains of material constituent phases decreases to nanometer or very fine, it is obvious that most of the usual mechanisms related to physical and mechanical properties do not work and the properties of material change dramatically [1].
Due to the need to improve the properties to increase the strength of advanced structures in the military, maritime, aviation, and medical industries, materials that have a high weight-to-strength

ratio are more likely to be needed. The most effective way to reduce the weight of the structure and increase its efficiency is to reduce the material density by 3 to 5 times more efficiently than the increase of the tensile strength, entry, or tolerance of failure [2].
To this end, the study of the mechanical properties of metals and their improvement has been studied by many researchers. In this regard, aluminum and its alloys are among the most important studies. The reason for this is the widespread use of this metal in the aerospace industry due to its unique individual properties [3].
Due to the increasing development of the military, maritime, aviation, and medical industries, the need to improve the properties of aluminum alloys, including achieving high strengths, is always felt while maintaining a low weight. Many researchers have tried to achieve high strengths in aluminum metal through mechanical alloying with elements such as manganese, magnesium, copper, silicon, and zinc. The main problem with this method is strengthening, the occurrence of small pores, and the possibility of cracking [4].
Altogether, factors such as impurities play a key role in determining the strength of aluminum due to the increased strength of the crystal lattice as well as the presence of structural defects including grain boundaries and misalignments [5].
According to the provided descriptions, it is necessary to provide and develop a suitable method to improve the mechanical properties of aluminum while maintaining its weight. In the last two decades, polycrystalline materials with very fine granulation to the extent of nanometers or several hundred nanometers (less than microns) have been highly regarded by researchers due to their special mechanical and physical properties. The mechanical and physical properties of crystalline materials are affected by several factors, the average size of which has a significant effect on the determination of these properties. In general, according to the relation (1) relation (Hall-Petch), the strength of the material is related to the reversed square of the grain size. In other words, as the grain size decreases, the strength of the material also increases [6].

$$\sigma_y = \sigma_0 + k_y d^{-\frac{1}{2}} \qquad (1)$$

In this relation, $\sigma_y$is the yield stress, σ_0 is the network resistance, d is the grain size, and k_y is the constant that depends on the material. (Hall-Petch coefficient)
One of the new approaches to the production of nanocrystalline materials and materials with very fine grains is the application of severe plastic deformation on the prototype with coarse grains. In this method, the grain size decreases to the nanometer scale in several stages by applying strong strains to the sample, and this improves the mechanical and physical properties of the material. These unique properties make this very fine material suitable for many commercial applications. Since changes in the dimensions of the material can be an obstacle to the amount of applied strain, most methods of applying severe plastic deformation have been designed in such a way that the dimensions of the sample remain constant during the process and do not change [6].
So far, there have been several processes for severe plastic deformation in metal materials and for achieving nanometer or very fine structures such as Equal Channel Angular Pressing (ECAP), Constrained Groove Pressing and Rolling (CGP and CGR), High-Pressure Torsion (HPT), Torsion Extrusion and Torsion after Extrusion (TE and TAE), Accumulative Roll Bonding (ARB), Equal-

Channel Angular Rolling Recently (ECAR), Multi-Directional Forging (MDF) and Twist Extrusion (TE).

The common and unique feature of most of these processes is that the dimensions are constant and the appearance of the material does not change during the process, which eliminates the restriction on the application of strain and makes it very easy to achieve very high strains in the material. Thus, by applying strain, it is possible to modify the microstructure, reduce the grain size to the nanometer scale, and improve the mechanical properties of the metal sample, while the shape of the sample does not change [7].

Another feature of these processes is increasing the strength and modification of grain structure without the addition of alloy elements or ceramic particles. One of the most important methods of applying severe plastic deformation is the CGP method, which has attracted the attention of many researchers in the last decade due to its special features [8].

The CGP process is an effective way to produce materials with very fine grains, thereby significantly improving their mechanical and physical properties [9,10].

Shin et al. [11] first used this process in the production of pure aluminum nanocrystalline sheets. Doing this process requires two sets of grooved mold and smooth mold. According to Figure (1), the geometric dimensions of the grooves of the mold are defined based on the width of the groove, t, and the angle of the groove θ. As can be seen in Figure 2, the cross-section of the grooved mold is asymmetrical. The process involves four steps:

Step 1: grooving the flat sheet under the press with the grooved mold (Figure 1-a).

Step 2: flattening the grooved sheet under the press with a flat mold (Figure 1-b).

Step 3: 180 degrees' rotation of the sheet (Figure 1-c) and re-grooving the flat sheet under the press with the grooved mold (Figure 1-d).

Step 4: Flattening the grooved sheet under the press with a flat mold (Figure 1-f).

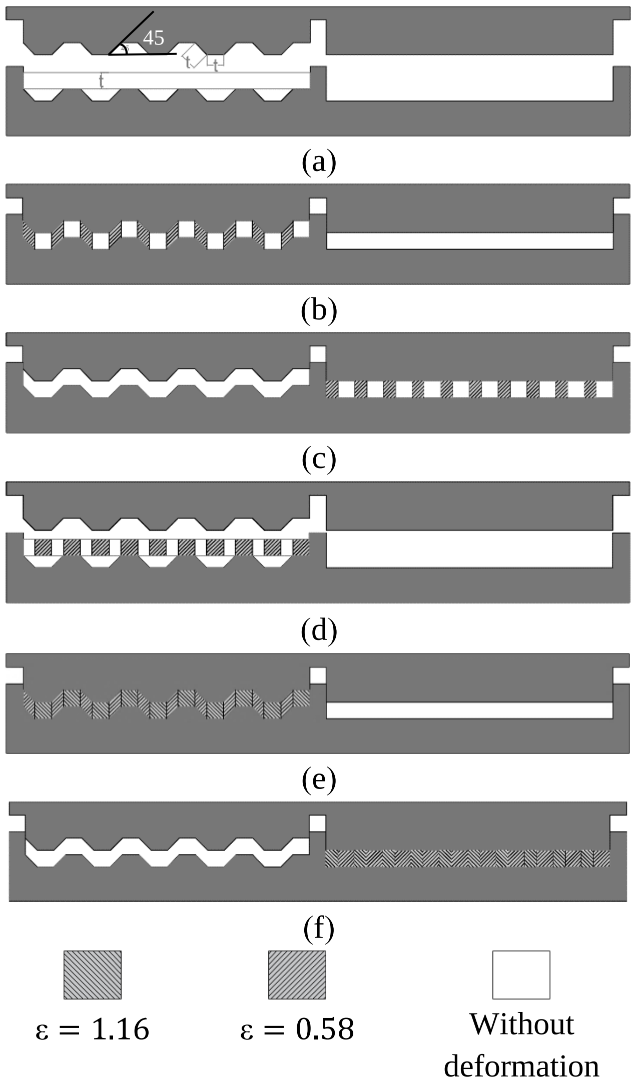

Figure 1. The geometry of the grooved and lattened die sections

In this process, the four consecutive pressing steps are called a pressing pass. Performing each pressing along with fine-tuning the sheet grains can increase the strength and hardness of the sheet, but as the number of passes increases, the effects of the process on improving the mechanical behavior of the sheet decrease, as well as creating surface cracks and reducing the ductility of the sample is one of the limiting factors in the number of passes that can be done for a sheet. The results of Sheen et al.'s study showed that grooved pressing of aluminum sheets, like other methods of severe plastic deformation, significantly improved the strength and stiffness of the samples. Therefore, the use of this method for the height of the properties of different types of alloys has attracted the attention of many researchers, which is not discussed here due to the brevity. The study of the effect of mold geometry on improving sample behavior has been very limited and sometimes contradictory.

By proposing a modified process (CGP with rubber mattress), Borhani and Javanroodi experimentally examined the effect of groove width and angle on the behavior of the nanocrystalline sheet. The results of their research showed that compared to the conventional 45-degree groove angle, the 50-

degree groove angle leads to a smaller structure of the sheet granulation. Although this improved the mechanical properties of the sheet, it did reduce the uniformity of strain in the final samples [12].

From an engineering design perspective, the uniformity of strain on the final sheet is important in terms of achieving high reliability and reducing probabilistic indeterminacy. By proposing the process (cover CGP), Sajjadi et al. showed that increasing the groove angle from 45 degrees to 53 degrees does not lead to a significant improvement in mechanical properties, and this change in shape reduces the number of passes that can be made on the sheet [13].

Peng et al. analyzed the effect of the mold groove width on the behavior of a copper and zinc alloy sheet under a CGP process. The results show that increasing the width of the mold groove from 5 mm to 7 mm leads to an increase in the number of press passes that can be made on the sheet before creating surface cracks. However this change in the mold has been accompanied by a decrease in the microstructure rate and a decrease in the level of hardening of the surface [14,15].

Rahimi et al. examined the behavior of pure aluminum deformation in CGP and RCS processes using finite element analysis. They observed that the amount of filling of the mold space in the CGP method was higher than that of the consecutive corrugating and flattening. Therefore, it is possible to repeat the process to achieve high values of plastic strain. Also, the deformed sample has been subjected to more strain by the CGP method than the other method. In addition, strain distribution is applied more uniformly in the sample [16].

Wang et al. examined the effect of mold geometry on the behavior of a pure nickel sheet under the groove pressing process. They simultaneously studied the effect of changes in the angle and width of the groove on the mechanical behavior of the sheet after the process. They used numerical process modeling to determine the optimal angle and width of the mold for groove pressing of a 2 mm thick sheet sample [17].

According to studies, little research has been done on weight loss without reducing the strength of advanced structures in the military, maritime, aviation, and medical industries. In this study, an attempt has been made to study mechanical behavior and strength by conducting experimental studies to eliminate this limitation and the possibility of developing studies on weight loss of advanced structures in the military, maritime, aviation, and medical industries due to changes in mechanical behavior.

2. Materials and Methods

2.1 Raw Materials

In this study, 7075 aluminum alloy was used. Since 7075 aluminum alloy has the ability of heat treating and high strength-to-weight ratio due to the small and uniform size of the secondary phase sediments in the network during the Precipitation hardening, by applying severe plastic deformation on it, it is a good option to replace with strong metals used in the military, maritime, aviation and medical industries [18].

In order to increase the strength and hardness and also to reduce the tensile corrosion resistance, T6 Precipitation hardening was performed during the process [19]. Also, the chemical composition of 7075 aluminum alloy was measured by the Spark Emission Spectroscopy (SES) and compared with ASTM B210 standard and shown in Table (1) [20]. In order to prepare a suitable sample for the

CGP process, cutting operations at the front page levels were performed. The sample was prepared by a cutting machine with a length of 20, a width of 9, and a thickness of 0.5 cm.

Table 1: The chemical composition of 7075 aluminum alloy compared with ASTM B210 standard

	Al	Zn	Mg	Cu	Fe	Si	Cr	Mn	Ti	Pb	Ni	V	Sb	Zr
WT. %	Bal.	5.11	2.46	1.22	0.523	0.45	0.14	0.104	0.021	0.021	0.15	0.002	0.002	0.001
WT. [20].	**%** Bal.	5.1 –6.1	2.1– 2.9	1.2 –2.0	0.50	0.40	0.18 – 0.28	0.30	0.20			0.15		

2.2 CGP process equipment

In this study, the simplest type of mold of the CGP process was used in such a way that it has two blocks and each has an asymmetrical grooved part that creates a shear deformation and also includes a flat mold that flattens the deformed piece. The dimensions of the mold include length 55, width 9, and height 20 centimeters. The dimensions of the groove in the grooved mold of 0.5 are equal to the thickness of the sheet and the angle of 45 degrees, which is created by machining operations. The material used to make the mold is AISI 1.6580 tool steel. To create the grooves in the mold, first machining operations were performed on the steel blocks, and then the mold was subjected to heat treating. At 860. degrees Centigrade, the mold was subjected to a dissolution operation for 80 minutes (including annealing, de-stressing, and hardening) and then cooled to perform a quenching operation in an oil environment. Re-baking was also performed at three temperatures of 210, 360, and 430 degrees Centigrade for 180 minutes and a hardness of about 50 Rockwell C was formed in the mold [21] (Figure 2).

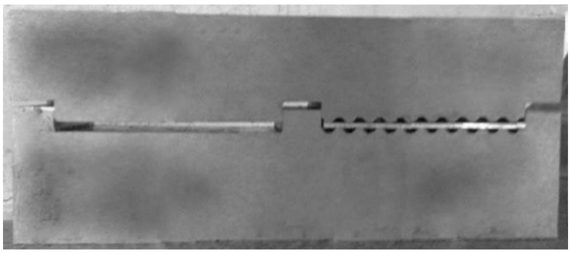

Figure 2. The Image template used

2.3 Effective strain of the sheet in each pass

In the multi-axis deformation of an element, the effective strain, ε_{eff}, is defined as the relation (2) according to the other strain components, so it can be:

$$\varepsilon_{eff} = \sqrt{\frac{2}{9}\left[(\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2\right] + \frac{4}{3}\left[{\varepsilon_{xy}}^2 + {\varepsilon_{yz}}^2 + {\varepsilon_{zx}}^2\right]} \tag{2}$$

Where ε_x ‹ε_y and ε_z are the normal strains in x, y, and z directions, as well as ε_{xy} ‹ε_{yz} and ε_{zx} are the shear strains on xy, yz, and zx, respectively. Due to Figure 3 in the CGP process, the sample is bound in the y-direction. Therefore:

$$\varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon_{yz} = \varepsilon_{zx} = 0 \quad (3)$$

In this case, we have:

$$\varepsilon_{eff} = \sqrt{\frac{4(\varepsilon_{xy})^2}{3}} \quad (4)$$

On the other hand, we have:

$$\varepsilon_{xy} = \frac{\gamma_{xy}}{2}\tan(\theta) = \frac{\gamma}{2}\tan(\theta) \quad (5)$$

According to Figure 3 and the studies performed, the height of the groove section is considered to be equal to the thickness of the sheet, in which case θ is equal to 45 degrees:

$$\gamma = \frac{x}{t} = \frac{t}{t} = 1 \quad (6)$$

In this case, the amount of shear strain in each pressing is equal to Equation (7).

$$\varepsilon_{eff} = \frac{\gamma}{\sqrt{3}} \xRightarrow{\gamma=1} \varepsilon_{eff} = 0.557 \quad (7)$$

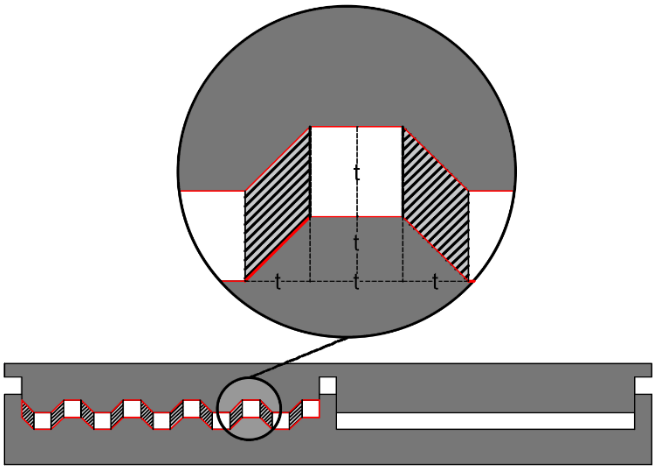

Fig. 3 The design of the deformed material in the CGP process

As shown in Equation (2-7), in each pressing, whether in a grooved or non-grooved mold, an effective strain of 0.557 is applied to parts of the sample, and by rotating the sample 180 degrees around the axis perpendicular to the surface of the sample (y-axis), this effective strain will be applied to the entire sample. Therefore, the effective strain at the end of each pass is calculated to be 1.114[22].

2.4 CGP process

In order to eliminate residual stresses and increase the strength and hardness of 7075 aluminum samples, they were subjected to 6T heat-treating according to ASTM B918-01 standard [23]. The samples were heated to 470 degrees centigrade for one hour and then cooled in water. The process was performed at a strain rate of s-1 10 at 120 degrees centigrade and to do that, the Instron 8502 Servo-Hydraulic Dynamic Testing System was used with a maximum load of 250 kN equipped with a furnace up to a temperature of 1000 degrees centigrade. First, they were placed in the furnace for 15 minutes, which had previously reached the desired temperature, to create the necessary temperature. After each flattening step, the 180-degree sheet was rotated clockwise and repositioned into the groove (Figure 4). Before the experiment, to reduce the friction between the mold and the sample, the mold grooves along with the sample were lubricated by MoS2 chemical lubricant [24].

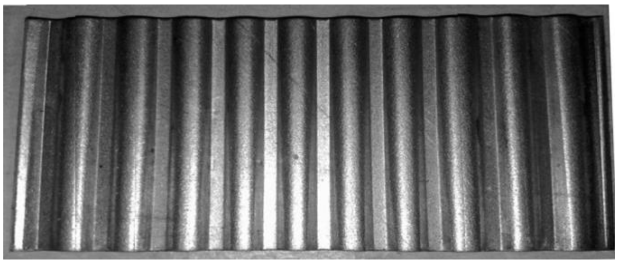

Figure 4. The sample image of CGP

2.5 Microstructure

The microstructure of the base metal cross-section and the 7075-T6 aluminum sample was studied under the CGP operation by an optical microscope manufactured by Sa Iran Company (IEI-IMM420 Microscope). Also, to evaluate the chemical composition of the existing sediments and the morphology of the surface of the samples, Carl Zeiss AG - Zeiss EM900 Transmission Electron Microscope (TEM) was used and the microstructure images were analyzed with MIP4student software.

2.6 Tensile testing

All samples were prepared for the tensile test according to ASTM E8/E8M-16a standard and reached the desired dimensions using a wire cut machine. The tensile test was performed at a constant rate of one millimeter per minute at ambient temperature for all samples and base metal [25].

2.7 Microhardness test

The Microhardness test was performed according to the ASTM E384-99 standard and based on the Vickers criterion with a diamond-shaped square depression and for this purpose, the depressing tip was performed on the midline of the transverse cross-section of the metallographic samples at a distance of 5 mm by applying a force of 50 N for 10 seconds by a hardness tester (DHV-1000 model) and the diagram of hardness changes was drawn for different samples [26].

3. Results and discussion

3.1 Microstructure

Figures 5 and 6 show the image of a light microscope from the transverse cross-sectional area of the prototype. As can be seen, the stretched grains from the rolling process, together with the MgZn2 needle-shaped sediments and the scattered distribution of other sediments, are among the aluminum grains, which can be seen as small black particles in Figure 5. The size of large grains in the sample is between 20 and 140 microns and fine particles are with a grain size of 10 microns, and the average grain size of this primary microstructure is about 60 microns based on the standard deviation method. As can be seen, after the CGP process, the crystal structure of the samples was significantly reduced by applying strain at each stage. After applying four steps of the CGP process, the UFG structure of the prototype has become a very fine grain structure and this grain size is very difficult to estimate (Figure 6).

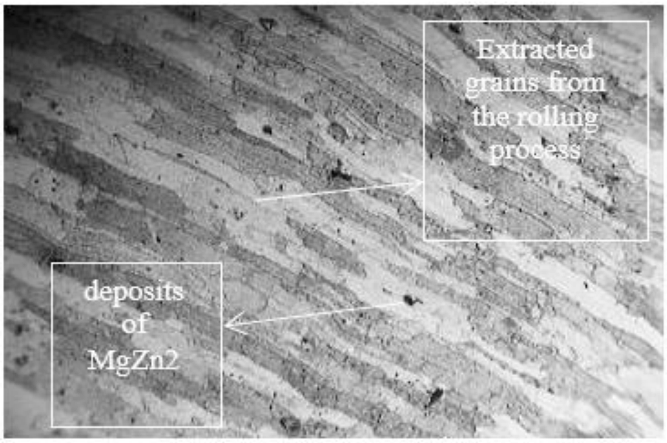

Figure 5. OM microscope image of the cross-section of free sample

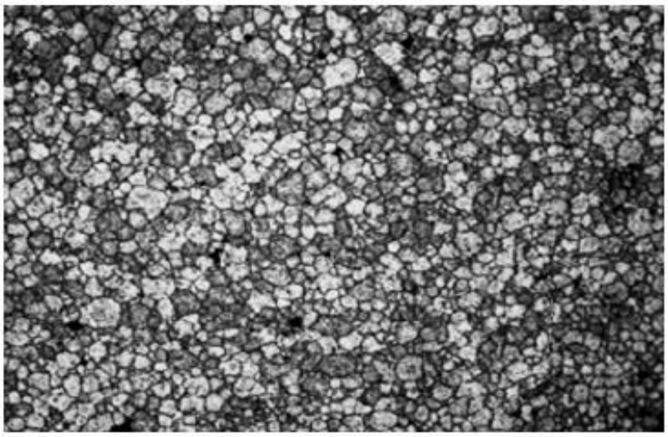

Figure 6. OM microscope image of the cross-section of pass 4 CGP process

Figures 7 and 8 show the image of the electron microscope passing through the surface of the 7075-T6 aluminum sample and the fourth pass of the CGP process, respectively. After four steps of applying the CGP process, the 7075-T6 aluminum coarse-grained prototype structure became a UFG structure with an average grain size of 270 nm.

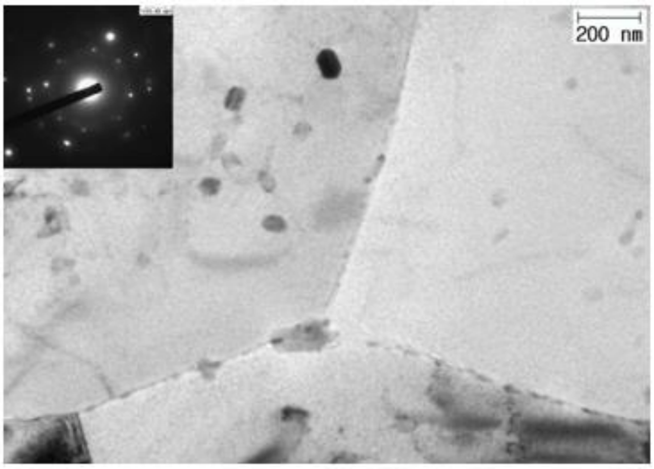

Figure 7. TEM picture of the cross-section of free sample

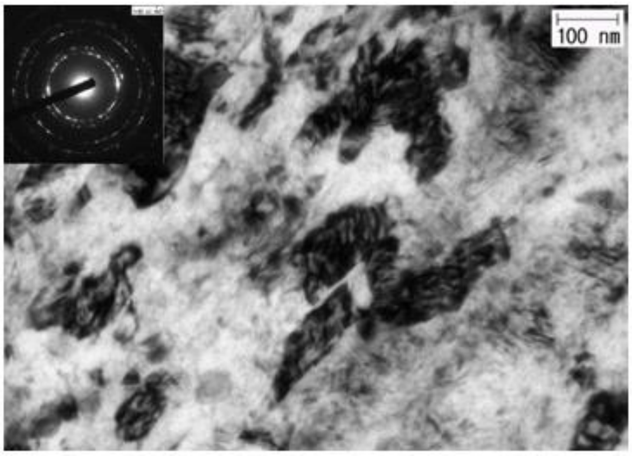

Figure 8. TEM picture of the cross-section of pass 4 CGP process

3.2 Micro Hardness test

The hardness changes in the samples are shown as a function of the number of steps in Figure (9) as well as the hardness values in terms of the longitudinal distance from one edge of the sample in Figure 10. As can be seen in Figure 9, the hardness of the 7075-T6 aluminum sample was approximately 157 Vickers, which in the first pass of the CGP process reached 214, in the second pass to 231, in the third pass to 243 and in the fourth pass to 254 Vickers. However the process of increasing the hardness in the first pass has been very large and with the increase of this pass, this trend has increased. According to Figure 9, it is observed that with increasing the number of passes of the CGP process, the degree of hardness uniformity has increased with the uniformity of mechanical properties.

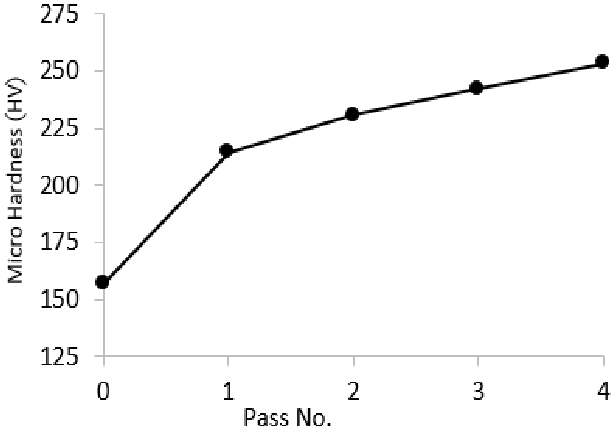

Figure 9. Hardness changes in samples as a function of the number

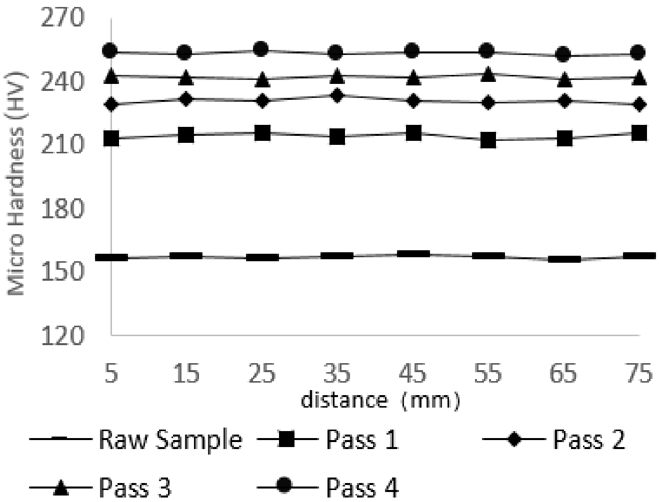

Figure 10. Hardness values in terms of long-distance from one edge of the sample

3.3 Tensile test

Figure 11 shows the changes in yield strength, tensile strength, and percentage of increase in length according to the number of passes for the CGP operations samples obtained from the single-axis tensile test for the prototype and the samples produced by the CGP process from the first to the fourth stage. As can be seen, in the first pass, the yield strength has increased from 512 MPa to 658 MPa or 25 percent. The tensile strength has also increased from 553 MPa to 657 MPa or 16 percent.

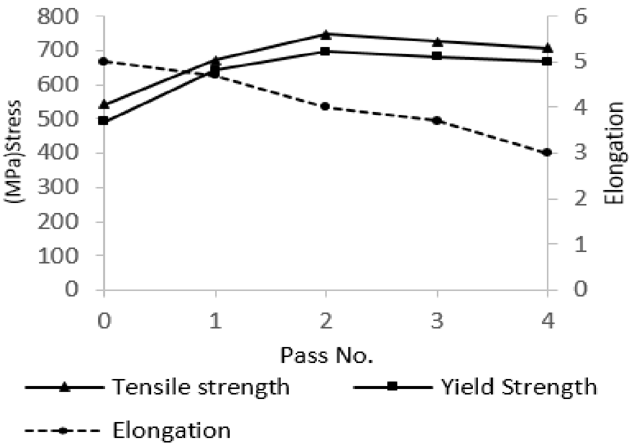

Figure 11. Strength of submission, tensile strength, and percent elongation

The percentage of the longitudinal increase in the first pass also decreases by 7%. The reason for this increase in the amount of yield strength and tensile strength, as well as the decrease in the amount of longitudinal increase, is the hardening of the sample in the first pass. In the fourth pass, the yield strength and tensile strength reach their highest value. The yield strength in the fourth pass increased by 38% compared to the annealed sample to 678 MPa and the tensile strength increased by 34% to 727 MPa. Also, the percentage of longitudinal increase in the fourth pass is reduced to its lowest value, ie 40%. According to Hall-Petch, the strength of materials depends on the size of their grains. Any changes in the size of the crystalline structure of the material cause significant changes in its strength and hardness. However, in the CGP process, large-angle grain boundaries are created with small size and strengthen the partition through the Hall-Petch relationship.

4. Conclusions

The CGP is a new process for the production of nanocrystalline materials of CGP that improves mechanical properties and thus optimizes the design of structures used in the military, maritime, aviation, and medical industries. 7075-T6 aluminum was subjected to this process up to 4 steps with a strain rate of s-1 10 at 120 degrees centigrade. The 7075-T6 aluminum microstructure has been reduced from 60 microns in the first stage to 270 nanometers in the last stage. Compared to the annealed sample, the yield strength in the fourth pass increased by 38% to 678 MPa, and the tensile strength increased by 34% to 727 MPa. Also, the percentage of longitudinal increase in the fourth pass is reduced to its lowest value, ie 40%. After the CGP process, the hardness of 7075-T6 aluminum increased so that by placing the material under severe plastic deformation in four stages, its hardness increases from 157 Vickers to 254 Vickers (about 62% of the prototype). On the other hand, the strength and hardness of matter have more or less the same trend.

5. References

[1] Zhilyaev, A.P. and Langdon, T.G. 2008. Using high-pressure torsion for metal processing: Fundamentals and applications. Progress in Materials science. 53(6):893-979.

[2] Ross, C.T. 2005. A conceptual design of an underwater missile launcher. Ocean Engineering, 32(1):85-99.
[3] Bai, X. 2013. Mineral image enhancement based on sequential combination of toggle and top-hat based contrast operator. Micron. 44:193-201.
[4] Naizabekov, A.B., Andreyachshenko, V.A. and Kocich, R., 2013. Study of deformation behavior, structure and mechanical properties of the AlSiMnFe alloy during ECAP-PBP. Micron. 44: 210-217.
[5] Xuebao , Z. D. 2011. Research on as-cast microstructures and properties of 3004 aluminum-manganese alloy. Journal of North University of China (Natural Science Edition). 32(4):523-528.
[6] Heidari, S., Afsari, A. and Ranaei, M.A. 2020. Increasing Wear Resistance of Copper Electrode in Electrical Discharge Machining by Using Ultra-Fine-Grained Structure. Transactions of the Indian Institute of Metals. 73(11): 2901-2910.
[7] Sieber, H., Wilde, G. and Perepezko, J.H. 1999. Thermally activated amorphous phase formation in cold-rolled multilayers of Al–Ni, Al–Ta, Al–Fe and Zr–Cu. Journal of Non-Crystalline Solids. 250:611-615.
[8] Shin, D.H., Park, J.J., Kim, Y.S. and Park, K.T. 2002. Constrained groove pressing and its application to grain refinement of aluminum. Materials Science and Engineering: A. 328(1-2): 98-103.
[9] Hajizadeh, K., Ejtemaei, S. and Eghbali, B. 2017. Microstructure, hardness homogeneity, and tensile properties of 1050 aluminum processed by constrained groove pressing. Applied Physics. A, 123(8):1-9.
[10] Fujda, M. and Kvacaj ,T. 2007. Microstructure and mechanical properties of EN AW 6082 aluminium alloy prepared by equal-channel angular pressing. Journal of Metals. Materials and Minerals, 17(2):23-27.
[11] Thangapandian, N., Balasivanandha Prabu S., Padmanabhan K.A. 2002. Effects of die profile on grain refinement in Al–Mg alloy processed by repetitive corrugation and straightening. Materials Science and Engineering: A, 649: 229-238.
[12] Borhani, M. and Djavanroodi, F. 2012. Rubber pad-constrained groove pressing process: Experimental and finite element investigation. Materials Science and Engineering: A, 546:1-7.
[13] Afsari, A., Ramezani, M., Heidari, S. and Karimi, J. 2020. Imperialist Competitive Algorithm (ICA) Approach for Optimization of the Surface Grinding Process. Journal of Modern Processes in Manufacturing and Production. 9(1): 51-62.
[14] Afsari, A., Heidari, S. and Jafari, J. 2020. Evaluation of Optimal Conditions, Microstructure, and Mechanical Properties of Aluminum to Copper Joints Welded by FSW. Journal of Modern Processes in Manufacturing and Production. 9(4): 61-81.
[15] Peng, K., Zhang, Y., Shaw, L.L. and Qian, K.W. 2009. Microstructure dependence of a Cu–38Zn alloy on processing conditions of constrained groove pressing. Acta Materialia. 57(18): 5543-5553.
[16] Rahimi, F., Mohammad, S.B. and Ahmadi, M. 2014. A comparative study between deformation behavior of pure Aluminum in CGP and RCS by finite element analysis. Metallurgical Engineering. 17(53):25-32.

[17] Wang, Z.S., Guan, Y.J., Wang, G.C. and Zhong, C.K. 2015. Influences of die structure on constrained groove pressing of commercially pure Ni sheets. Journal of Materials Processing Technology. 215: 205-218.
[18] Handbook, A.S.M. 1990. Properties and selection: irons, steels, and high-performance alloys. ASM international 1:140-194.
[19] Park, J.K. and Ardell, A.J. 1983. Microstructures of the commercial 7075 Al alloy in the T651 and T7 tempers. Metallurgical Transactions A. 14(10):1957-1965.
[20] Heidari, S., Bakhshan, Y., Khorshidi Mal Ahmadi, J. and Afsari, A. 2019. Investigating the Behavior of Aluminum 7075 under the Process of CGP as the Fin of Space Structures. Modares Mechanical Engineering, 19(5):1187-1197.
[21] Designation: B918-01, Standard Practice for Heat Treatment of Wrought Aluminum Alloys. 2003. The Annual Book of ASTM Standards. Section 03. ASTM International, United States.
[22] Shirdel, A., Khajeh, A. and Moshksar, M.M. 2010. Experimental and finite element investigation of semi-constrained groove pressing process. Materials & Design. 31(2): 946-950.
[23] Designation: B918-01, Standard Practice for Heat Treatment of Wrought Aluminum Alloys. 2003. The Annual Book of ASTM Standards. Section 03. ASTM International, United States.
[24] Quan, G.Z., Li, G.S., Wang, Y., Lv, W.Q., Yu, C.T. and Zhou, J. 2013. A characterization for the flow behavior of as-extruded 7075 aluminum alloy by the improved Arrhenius model with variable parameters. Materials Research. 16(1):19-27.
[25] ASTM International. 2016. E8/E8M-16a: Standard Test Methods for Tension Testing of Metallic Materials. ASTM international.
[26] ASTM, E. 1999. 384-99. Standard Test for Micro indentation Hardness of Materials, ASTM International.