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The Effect of the Constrained Groove Pressing Process on Mechanical Properties of Thin Pure Copper Sheets

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Abstract

Thin copper sheets with micro-dimensional thickness are increasingly used in forming processes. Copper is widely used in electronic industries and in many cases, it is required in the form of thin sheets with a thickness of less than 1 mm. However, decreasing the thickness of the sheet and extending its order to grain size leads to some problems such as dispersion of laboratory results and reduced material strength. In this study, an attempt has been made to improve the mechanical properties of copper sheets by applying the cold working method of Constrained Groove Pressing (CGP). By applying the accumulated plastic strains, the grain size decreased and the ratio of the sheet thickness to the grain size increased, thereby the mechanical properties of the sheet were improved. The results show that the application of the CGP process increases the ultimate strength up to 25% and the yield stress up to 114%. Moreover, it reduces the maximum strain up to 77% and increases the hardness up to 100%. The cross-sectional images taken by an optical microscope show changes in grain density and size under this CGP process. A finite element (FE) simulation has been performed to investigate the effect of the CGP process on the micro deep drawing process. The obtained results show a decrease in the Limiting Drawing Ratio (LDR) from 1.96 for as-received material to 1.7 for one pass and two passes and to 1.34 for three passes CGPed blank. Furthermore, a uniformity in shell thickness (STH) was observed along the cross-section of the blank.

Nomenclature

$\gamma_{ij} \cdot \varepsilon_{ij}$	Shear strain, Half of shear strain	SN	Strain
ε_{eff}	Effective strain	STH (mm)	Section thickness
ε_i	Normal strain	t (mm)	Width and depth of the groove
$\theta(^\circ)$	Groove angle	US (MPa)	Ultimate strength
AR	As received (material)	YS (MPa)	Yield strength
d(mm)	Thickness of the sheet	1P, 2P, 3P	1, 2, and 3 passed of CGP
LDR	Limit of drawing ratio		

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1. Introduction

Today, micro forming processes have received a lot of attention due to their low production costs and high added value, and the use of copper sheets with under 1-millimeter thicknesses in industries such as the electronics industry is increasingly expanding. However, apart from dimensional and tolerance parameters, the field of micro forming has other challenges as well. Reducing the thickness of the sheet to grain size reduces the number of grains in the thickness direction, which leads to problems such as dispersion of results and decreased sheet strength. Although not much effort has been made in the micro field to solve this problem, many studies have been conducted on methods of reducing grain size and thus increasing the ratio of thickness to grain size in macro dimensions. One of these methods is a cold working process called CGP which is based on the accumulation of severe plastic strains, which in turn reduces the grain size and thus improves the mechanical properties of the sheet. The CGP process was first introduced in 2002 by Shin et al. [1]. Their study was about the effect of the CGP process on the change in aluminum grain size. At the beginning, they performed this process with the aim of making changes to the microstructure of the material, without changing its dimensions and by creating severe shear plastic strains. In 2002, Lee et al. [2] investigated the effect of the CGP process on aluminum sheets numerically and experimentally. They studied microstructural changes through the thickness of the sheet and concluded that the shape and size of the grains in the center of the plate were different from its surfaces. In another result, Lee found that as the number of passes increased, the grain shrinkage process slowed down and stopped. In 2010, Niranja et al. [3] studied the effect of CGP on the deep drawability of pure commercial aluminum sheets. Their studies showed that in metals such as copper and aluminum, the drawing ratio is small, while the use of the CGP process resulted in more drawability. Some processes were also defined in subsequent years with minor changes. In 2009, Shirdel et al. [4] prepared the semi-CGP process by laboratory methods and finite elements. This process is very similar to CGP, except that only the two side edges of the sheet are restrained and the end edges expand freely. In this study, after enduring the process, the sample was subjected to hardness and tensile tests and its mechanical properties were measured. Moreover, the FE simulation of the process has been performed with the aim of checking the plastic deformation of the material. In 2011, Morattab et al. [5] investigated the mechanical properties and microstructure of pure aluminum under the GP process. The only difference between CGP and GP was that the boundaries of the sheet under deformation were not constrained in GP. The GP process was performed in four passes. Yield and ultimate stresses increased by 2.3 and 1.5 times, respectively, by the end of the third pass, and decreased slightly in the fourth pass. The hardness also increased continuously from 26 Vickers at the beginning to 40 Vickers by the end of the fourth pass. The material retained its ductility to some extent. In 2011, Peng et al. [6] studied the equivalent strain, hardness, and microstructure of the brass alloy under the CGP process. In 2012, Sajadi et al. [7] investigated the properties of aluminum undergoing the CGP process. To avoid the effects of stress concentration due to the impact of the sharp edges of the die with the sheet and also to prevent the growth of micro cracks, low-thickness copper sheets were used as an intermediary between the die and the aluminum sheet. This method was introduced as the cover sheet casing (CSC). The parameters studied in this study included strength, hardness, and increase in failure length, which showed acceptable results in the mentioned parameters. Improving the results was so acceptable that this method could be introduced as a suitable alternative to the usual CGP processes. Then, the FE model of the work was studied and the results were compared with the experimental data, which had shown an acceptable proximity. In 2012, Borhani et al. [8] examined the CGP process experimentally and numerically by replacing a rubber pad with the top die. Experiments were performed for two groove angles of 45 and 50 degrees. The results showed that the hardness increases significantly (up to 55 Vickers). In 2013, Satish et al. [9] examined the grain size of pure aluminum sheet under the CGP process. The results demonstrated an increase in yield stress and tensile strength and by increasing the number of passes to 3 and more, the occurrence of dynamic recovery phenomenon caused a slight decrease in stresses.

Dynamic recovery is a phenomenon caused by an excessive increase in the displacement of dislocations, which causes the properties of the material to decrease, and the grain size increases by rejoining the dislocations. In the CGP process, this phenomenon occurs with increasing the number of passes and causes a reversal of the trend of changes in the mechanical properties of the material and its microscopic geometry. In 2014, Ghazani et al. [10] conducted an FE study about the effect of CGP on the properties of aluminum alloy. Simulations were performed for 1% magnesium aluminum alloy, and the focus of the results was on the inhomogeneity of plastic deformations in the longitudinal direction of the sheet. In 2017, Vaidyanathan et al. [11] investigated the deep drawing of constrained groove pressed steel sheet. In this study, they measured the LDR of a steel sheet for different passes of the CGP process including raw material, first pass, and second pass. The results did not show a significant difference. Moreover, the results of the hardness test showed a relative improvement in the hardness of the material after the second pass. Overall, the result of this study showed that applying two passes of the CGP process on the steel sheet led to the production of a deep drawn product with a relatively better hardness without having much effect on the LDR.

More recent researches have examined other areas of the process. For example, in 2018, Nazari et al. [12] calculated the press force required to perform the CGP process. For this purpose, they performed their experiments on three different materials with two different geometries and used different models such as von Mises and Tresca to predict the behavior of the material. Also, in 2019, Ghorban Hosseini et al. [13] conducted a new study. In this study, the CGP process was applied for one, two, and three passes, which yielded interesting results. The amount of anisotropy in the first pass showed the highest value, also the hardness of the material in the first pass increased by 65%, which was about 27% for the next passes. The amount of increase in length in the tensile test did not differ much for the three passes compared to the initial material. The mean hardness measured for five points of the sample showed that the inhomogeneity for the two passes results in the lowest number, and finally the highest ultimate strength was recorded for the first pass, and the next passes resulted in a decrease in the ultimate strength. The CGP process can be implemented in different ways. The classical route method is the most common; however, other methods such as the cross-route method have also been studied. In 2019, Moradpour et al. [14] compared the classical and cross-route methods in an aluminum-magnesium sheet and simulated the two methods. The results showed that the cross-route method had more homogeneity and uniformity compared to the classical one. The cross-route method, however, involved more steps and took a longer time. In 2020, Dehghanapour et al. [15] investigated the effect of the CGP process on the mechanical properties and formation of intermetallic phases at the boundary of the layers for cold roll bonded Al-steel bilayer sheets. In 2021, Sean et al. [16] studied the microstructure and mechanical properties of 316 austenitic steel under the CGP process. The results showed that the structure of the metal changed to martensite and that the mechanical properties of the metal such as maximum stress, yield stress, and hardness increased. In 2021, Kumar et al. [17] made a comparison between the numerical and experimental results of morphology and mechanical behavior of copper and aluminum sheets and presented a numerical model to predict the behavior of the material under the CGP process.

Despite numerous works that have been done in recent years to investigate the effect of the CGP process on the mechanical properties and behavior of materials with thicknesses in macro dimensions, no study has been carried out so far in the field of thicknesses with micro dimensions, while the use of such sheets in the electronics and medical industries is considerably wide. Micro-dimensional sheets show different behavior under the influence of processes such as CGP due to the facts that the thickness of the sheet is close to the grain size of the material on one hand and that the ratio of surface to volume is large on the other hand. The present study aims to experimentally study the effect of the CGP process on characteristics of a very thin copper sheet (i.e., with micro-order in thickness).

2. CGP Process

CGP is a kind of severe plastic deformation (SPD) method which is suitable for metal sheets and has advantages such as fixed dimensions and non-rupture of the raw material compared to other SPD methods. In this method, the metal sheet undergoes shear stresses under the pressure of the grooved dies first and then returns to its original shape under the pressure of the flat dies. Creating accumulated strains in the material causes its structure to become fine and new grain size with smaller dimensions to form. Fig.1 shows a schematic view of this process. First in (1-b), the hatched part is strained and the white area remains without strain. Then in (1-c), the material returns to its original shape and the parts marked with mesh accumulate strain while the other parts remain without strain. After that in (1-d), the metal plate rotates 180 degrees around the axis perpendicular to the plate and in the new position during (1-e) and (1-f), the non-deformed parts of the plate also undergo the same shear strains evenly. These steps are all defined as one pass [1].

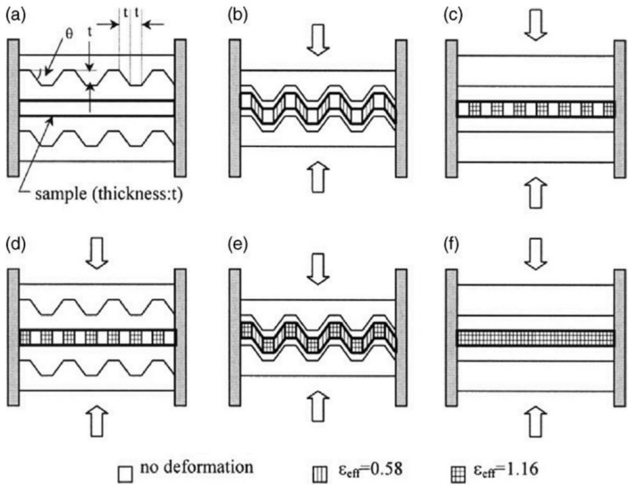

Fig. 1. Schematic illustration of the sequences of the CGP process [1].

The CGP process may be performed in one pass or more. In this method, the outer borders of the plate are constrained by the walls [1]. So far, many attempts have been made to investigate the effect of the CGP process on the properties of the material. However, no serious studies have been conducted in the field of micro or the challenges of using this method in sheets with a thickness of less than one millimeter.

This method has been performed for various materials such as aluminum, copper, and their alloys. A set of asymmetric grooved dies with a groove angle (θ) of 45 degrees and a width and depth (t) equal to the thickness of the sheet (d) was used to create shear strains ($\gamma_{xy} = 1$) on the sheet. The effective strain created by this shear strain would be 0.58 (Equations 1 to 6 [3]). In the next step, the sheet was subjected to shear strain again by smoothing using a flat die, and as a result, the accumulated shear strain reached 1.16. By rotating the sheet 180 degrees around the axis perpendicular to the plate and repeating the process, other parts of the sheet would undergo the same shear strain. Increasing the number of passes increased the accumulated shear strain so that after the end of the second, third, and fourth passes, these values reached 2.32, 3.48, and 4.64, respectively.

$$\gamma_{xy} = \frac{t}{d} = \tan 45^\circ = 1 \quad (1)$$

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

$$\varepsilon_{xy} = \frac{\gamma_{xy}}{2} \quad (3)$$

$$\varepsilon_x = \varepsilon_y = \varepsilon_{yz} = \varepsilon_{zx} = 0 \quad (4)$$

$$\varepsilon_{eff} = \sqrt{\frac{4}{3}(\varepsilon_{xy}^2)} \quad (5)$$

$$\varepsilon_{eff} = 0.58 \quad (6)$$

One advantage of using the CGP process is a reduction in the grain size of metal plates in the direction of thickness and thus a decrease in the inhomogeneity and anisotropy. By changing the grain size, the arrangement of deformations and grain boundaries, the density of grain boundaries, and the ratio of inner dislocations to surface ones, properties of the material such as strength and hardness can be changed. By reducing the grain size in terms of thickness and increasing the ratio of thickness to grain size, the dispersion of the results gathered from different tests is reduced. However, reducing the thickness to the sub-millimeter level increases the surface-to-volume ratio of the sheet and the sensitivity of the sheet to surface defects. The material used in this study was pure copper sheet with a thickness of 0.1mm and the percentage of sheet elements is given according to quantometer analysis (resulted from the tests) in Table 1.

The tensile test specimen was cut from the as-received sheet according to ASTM E8 standard. Due to the low thickness of the sheet and in order to prevent the occurrence of local defects through the cutting lines, the wire-cut method was used to prepare the tensile test specimen. The tensile test specimens were cut at two angles of 0 and 90 degrees with respect to the rolling direction. The test results are shown in Fig. 2. The tension test was performed by a Zwick machine with 1 micron in extension and 0.1 newton in force accuracy.

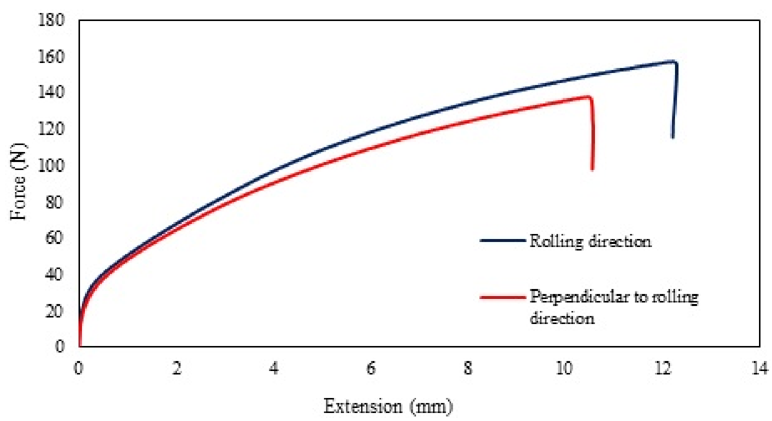

Fig. 2. Tensile test diagram for pure Cu in rolling and perpendicular directions.

Table 1
Percentage of elements in the pure copper sheet.

Element	Zn	Pb	Fe	Ni	Al	Si	Mn	Cu
Percentage	0.033	0.003	0.015	0.014	0.001	0.004	0.002	99.927

Comparing the results of the tensile test of the specimens prepared from the sheet, which were cut at angles of zero and 90 degrees with respect to the rolling direction, shows that the problem of anisotropy is not very evident in the existing copper sheet; therefore, the effect of this parameter and its study is neglected. As mentioned before, a very thin copper sheet would be deformed and no kind of lubricant is used because of limitations and possible adverse effects. The geometry of the deformed sheet is a 100mm×30mm rectangle. Due to the high tolerance sensitivity, the CGP grooves created on the die are limited to a 40mm×30mm rectangle and the rest of the die surface is without grooves. The process is performed in three stages of one, two, and three passes and for two samples in each stage. Then, the dumbbell sample cut from the sheets was subjected to tensile test. The result of the tensile test is shown in Fig. 3.

3. Micro Deep Drawing

To investigate the application of the CGP process, an FE simulation of the micro deep drawing (MDD) process has been set to observe the effect of changes in mechanical properties of the sheet, during the CGP process, on the MDD characteristics such as LDR, drawing force, and thickness uniformity. The MDD process includes a copper blank with 10mm in diameter and 0.1mm in thickness, a punch with 4mm in diameter, a blank holder, and a die. To reduce the calculation time, one fourth of the geometry is simulated and symmetric boundary condition is used to generalize the results for all of the geometry. The friction coefficient and punch velocity are assumed as 0.08 and 1mm/s, respectively. The size of S4R mesh in blank after convergence tests is selected as 0.18mm.

4. Results and Discussion

Examination of the extracted diagrams, in general, shows the extent to which the CGP process affects the strength and ductility of the copper sheet. The increase in yield and ultimate stresses and the decrease in strain can be seen most clearly in the diagrams. Fig. 4 shows the maximum strain changes, yield stress, and ultimate stress of tensile test specimens for different passes. The diagram depicts that as the passes increase, the maximum strain of the copper sheet decreases, which means less ductility. In contrast, the yield stress and the ultimate stress increase, which means an increase in the strength of the copper sheet during the CGP process.

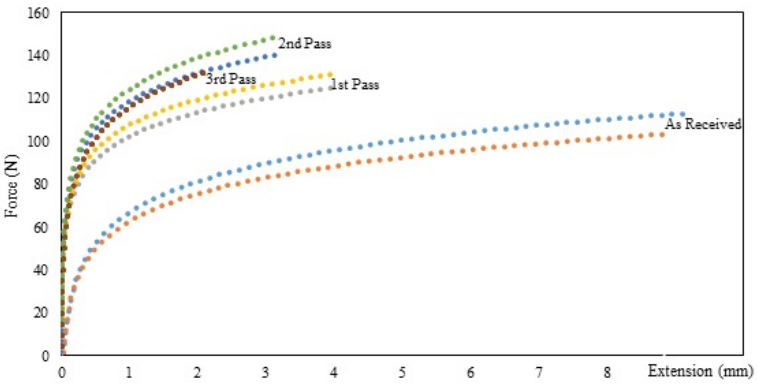

Fig. 3. Results of tensile test for different passes of CGPed sheets.

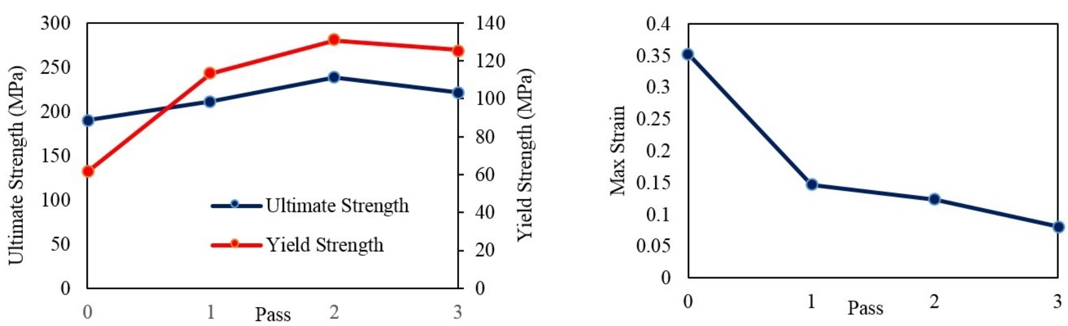

Fig. 4. Ultimate and yield strength and maximum strain for different CGP passes.

Table 2 lists the values of maximum strain, ultimate stress, yield stress, and hardness for different samples and passes of the copper sheet under CGP. It is noteworthy that the increase in yield and ultimate stresses is up to the second pass and the third leads to a decrease in them. As can be seen in Table 2, each of the CGP passes was performed on two samples of copper sheet to examine the dispersion of the results, and the results of this study are shown in Fig. 5. The effect of the CGP process on the hardness of copper sheet is shown in Fig. 6 in which the unit of measurement is Vickers.

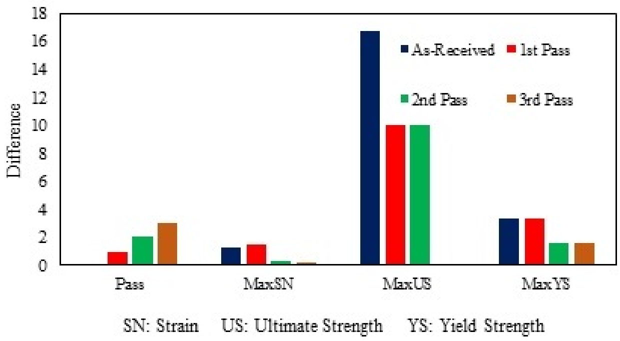

Fig. 5. Difference in maximum strain (x100), ultimate strength, and yield strength for different passes.

The study of images taken from the cross-section of the sheets by the optical microscope shows that the grain size and grain density undergo significant changes under the influence of the CGP process. Finally, Fig. 7 addresses the results of MDD simulations. Fig. 8 shows the contour of thickness of the cup for four steps of processing including: As-received material, 1-pass CGPed, 2-pass CGPed, and finally 3-Pass CGPed materials. There have been five numbered zones along the section which refers to flange zone of the blank, die radius, wall of the cup, punch radius, and bottom of the punch, respectively. As can be seen, the sheet thickness has increased in zones number 1, 2, and part of 3. By passing through the zone number 3 the thickness starts to decrease and the maximum decrease occurs in zone number 4 (punch radius).

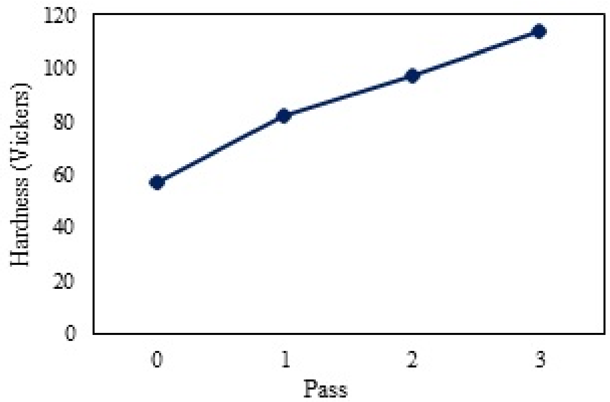

Fig. 6. Hardness in Vickers for different passes.

Table 2
Maximum strain, ultimate stress, yield stress, and hardness values for copper sheet samples.

	As-Received			1st Pass			2nd Pass			3rd Pass		
	Sample 1	Sample 2	Ave.	Sample 1	Sample 2	Ave.	Sample 1	Sample 2	Ave.	Sample 1	Sample 2	Ave.
Maximum Strain	0.359	0.346	0.353	0.139	0.155	0.147	0.122	0.126	0.124	0.080	0.082	0.081
Ultimate Stress (MPa)	198	182	190	207	217	212	233	243	238	222	222	222
Yield Stress (MPa)	63	60	61.5	112	115	113.5	130	132	131	127	125	126
Hardness (Vickers)	55	59	57	79	85	82	100	94	97	110	118	114

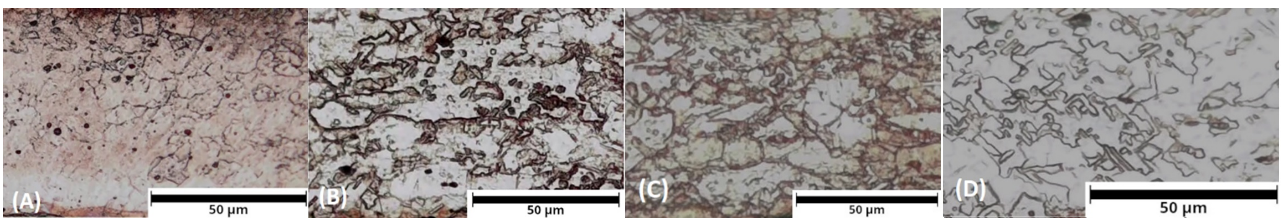

Fig. 7. Grain size of cross-section section of the blank, a) As-received, b) 1 Pass, c) 2 Passes, d) 3 Passes.

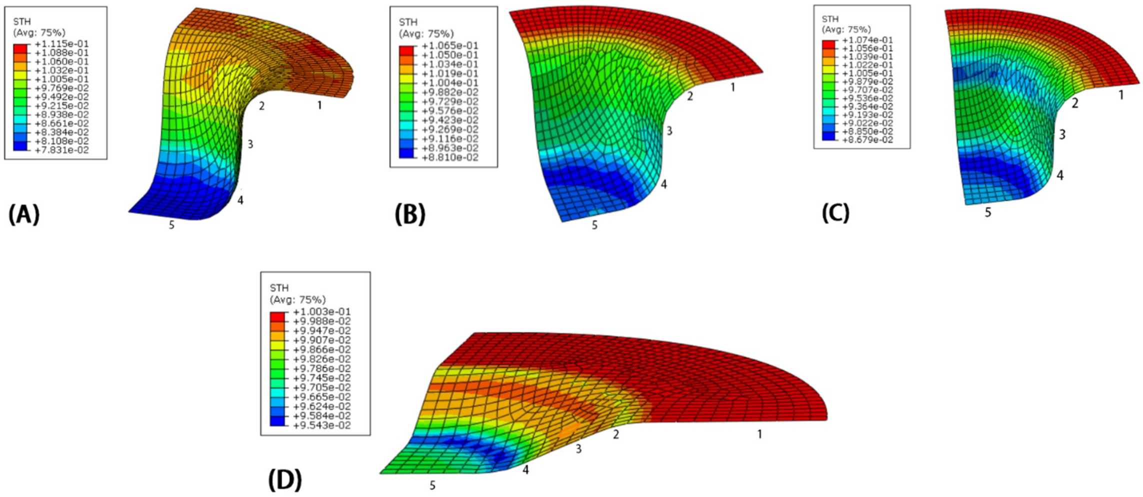

Fig. 8. STH contour for different CGP passes, a) As received, b) 1 pass, c) 2 passes, d) 3 passes.

Table 3
LDR and Drawing Force Max. for different CGP passes.

	As-Received	1 Pass	2 Passes	3 Passes
LDR	1.96	1.7	1.7	1.34
Drawing Load Max. (N)	68.1	67.7	72.8	64.6

Fig. 9 compares the change in the thickness of the blank through the cross section for different passes of CGPed blanks. The results show that by repeating the CGP process, the uniformity in thickness increases.

Finally, the change in two important parameters that are LDR and Drawing Load Max through the CGP process are investigated. Table 3 includes the measures of LDR and Drawing Load Max for different CGP passes and as-received material.

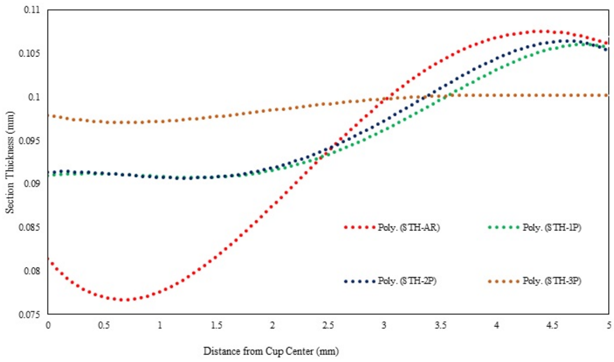

Fig. 9. Change in section thickness for different passes of CGP process, AR: As Received, 1P: 1 Pass, 2P: 2 Passes, 3P: 3 Passes.

As expected, applying the CGP process, which is a type of SPD process, increases the ultimate strength (12% in the first pass, 25% in the second, and 17% in the third one), increases the yield strength (85% in the first pass, 114% in the second, and 105% in the third one), and reduces the maximum strain (58% in the first pass, 64% in the second, and 77% in the third one) of the annealed copper sheet, which occurs due to the work hardening phenomenon or strain hardening phenomenon. It was observed that until the second pass, the gradient of changes in the ultimate and yield strength was increasing, but it decreased in the third pass. This decrease is expected due to the dynamic recovery phenomenon. Dynamic recovery is a phenomenon that occurs with an increase in the density of dislocations, which were created under the stress part, and causes a decrease in the strength of the material [18].

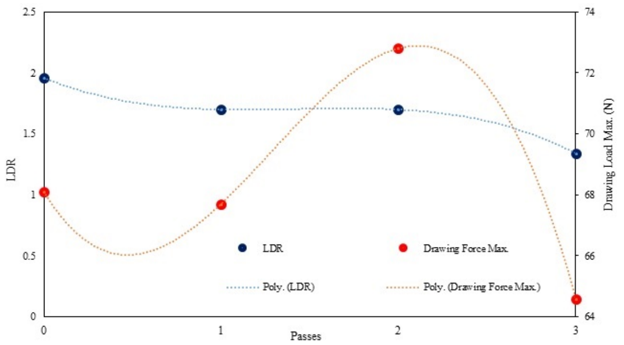

Fig. 10. Change in LDR and Drawing Load Max. for different passes of the CGP process.

This is the dominant phenomenon compared to the hardening phenomenon from the third pass onwards and it prevents the increase in the strength of the material. Moreover, the hardness of the copper sheet increases with the increase in the number of repetitions and it reaches 82 Vickers in the first pass, 97 Vickers in the second pass, and 114 Vickers in the third one. The results obtained from previous studies in macro dimensions confirm this continuous increase in the hardness

[19, 20, and 21]. The dispersion of the results generally decreases with the increase in the number of repetitions, which means that the mechanical properties of the material become more uniform due to the reduction in the grain size.

The results of the optical microscope images taken from the cross section of the copper sheets displayed in Fig. 7 show that by applying the CGP process on the copper sheet, the grain size and the grain boundary density change. The sheet subjected to one CGP repetition (8B) demonstrates a smaller grain size and higher grain boundary density compared to the original sheet (8A). This decrease in the grain size and increase in the grain boundary density have also continued in the second pass of CGP (Fig. 8C), and this decrease in the grain size and increase in the grain boundary cause an increase in the yield and ultimate strength of the material. However, as seen in Fig. (8-D), in the third pass of the CGP process, due to the dynamic recovery phenomenon, the size of the grains increases again and the density of the grain boundaries decreases, and as a result, the yield and ultimate strength of the material also decrease. Finally, the simulation results , focusing on the effect of the CGP phenomenon on the stress-strain diagram of the material, show a reduction in the LDR and an increase in the uniformity of the drawn sheet thickness by increasing the number of repetitions of the CGP process; whereasit does not have much effect on the Drawing Load Max.

5. Conclusions

The behavior of the material in very thin thicknesses and in micro dimensions poses challenges that are practically not accounted for in macro dimensions. The significant size of the grains compared to the thickness of the sheet on one hand and the large ratio of the surface to the volume of the sheet on the other hand cause a deviation in the test results and also increase the dispersion of the results. Comparing the changes made in the mechanical properties of the micro copper sheet (0.1mm in thickness) with a macro copper sheet (1mm in thickness) under the CGP process, despite the confirmation of the general results such as the increase in the ultimate and yield strength, the decrease in the maximum strain, and the increase in the hardness, shows some differences:

1. The effect of dynamic recovery in the sheet with macro dimensions dominates from the third repetition and prevents the increase in the strength of the sheet. For the copper sheet with micro dimensions, this happens from the third repetition too.

2. The maximum ultimate strength for the copper sheet with micro thickness occurs in the second pass which is 238 MPa. For the copper sheet with macro thickness it takes place in the second pass which is 260 MPa. The increase in the ultimate strength for the micro sheet compared to the raw material (190 MPa) in the first pass is 12

3. The maximum yield strength for the copper sheet with micro dimensions in the second pass is 131 MPa and it is 228 MPa for the copper sheet with macro thickness in the second pass. The increase in the yield strength for the micro sheet compared to the raw material (57 MPa) in the first pass is 44

4. The maximum strain for the micro copper sheet in the third pass is 0.08, which is 0.14 for the macro sheet in the same third pass. Compared to the maximum strain of the raw material, the micro sheet shows a decrease of 77

5. The FE simulation results show that the cold-worked sheet under the CGP process has a lower LDR than the raw material while recording greater uniformity in the thickness of the cup. Of course, it should be noted that the simulation results are only valid if the changes in the stress-strain diagram are considered to be caused by the CGP process and the effect of grain size change on the drawability of the material is not taken into consideration.

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