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Influences of the constrained groove pressing on microstructural, mechanical, and fracture properties of brass sheets

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Abstract

Constrained groove pressing (CGP) was used for the production of fine-grained brass sheets in different conditions. The process was conducted up to two cycles on brass sheets at room temperature and then half cycle at the temperature of 200 °C. Optical microscopy (OM), scanning electron microscopy (SEM), microhardness measurement, and plane stress fracture toughness was used to investigate the microstructure, mechanical properties, and fracture behavior. Microhardness measurement showed the capability of the CGP process in increasing the hardness of the refined sheets. It also showed the inhomogeneity of the hardness along the thickness of the sample after the process. The Digital Image Correlation (DIC) technique was used to investigate the elastic and plastic factors of the sheets along with the major mechanical properties of samples. The results showed a slight increase and reduction in the Young modulus and Poisson’s ratios after the process, respectively. Moreover, after two CGP cycles applying half cycle at the temperature of 200 °C did not show any significant effect on these values. The strength coefficient was as like as yield and ultimate strengths increased by increasing the number of the passes. However, processing at a higher temperature of 200 °C showed lower values for the parameters, as mentioned earlier, compared to the specimens processed at room temperature. The strain hardening index experienced a major reduction after the CGP process due to the effects of strain hardening. The anisotropy coefficient, which plays a critical factor in the severe deformation of sheets, was increased after the CGP process. However, this ratio decreased in higher passes or elevated temperatures. The highest anisotropy coefficient was obtained after the first cycle of the process. Moreover, SEM observation of the fracture surface showed shearing ductile rupture mode in the processed samples rather than ductile mode due to appearing of small and elongated dimples.

1. Introduction

Improving the mechanical properties of metals and alloys provides a good opportunity for their usage in various industries [1, 2]. One of the ways for obtaining the materials with superior mechanical properties is by decreasing the average grain size of them to the ultrafine grain (UFG) ranges [3]. On the other hand, it has been shown that grain refinement can be easily achieved after performing different severe plastic deformation (SPD) techniques on the materials [4, 5]. Performing these kinds of methods on different alloys causes work hardening, grain refinement, and increasing dislocation density, which can count as the reasons for improving the strength of the materials [6]. There are various SPD methods, which have been introduced during the last two decades and are used for producing ultrafine-grained rods, tubes, and sheets. The most frequent methods are equal channel angular pressing (ECAP) [7, 8], cyclic extrusion compression (CEC) [9, 10], high-pressure torsion (HPT) [11, 12], accumulative roll bonding (ARB) [13, 14], and constrained groove pressing (CGP) [15, 16].

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Among these processes, ARB and CGP are used, especially for producing UFG sheets. Between these two techniques, the ARB has a difficult initial preparation. Also, it was mentioned in the papers that for proper bonding, parameters of the process must be carefully determined \[17\].

In contrast, the CGP process doesn’t require surface preparation for bonding between two surfaces and imposes more uniform deformation on sheet metals, which doesn’t change the cross-sectional shape of the sample \[18, 19\]. Moreover, the de-lamination problem is seen in the ARB produced sheets, which can be omitted in the CGP process \[18, 20, 21\]. In the CGP process, higher amounts of plastic shear deformation are applied to the specimen between the asymmetrically grooved and flat dies, alternatively. Figure 1 shows the CGP process, which consists of four steps. In the first step, the sheet is deformed inside the grooved die, which applies strain to the portions of the specimen; in the second step, the deformed sheet is located in a flat die and revenues to its primary shape. In order to apply strain to the whole points of the sheet, in the third step, the sheet is rotated 180 degrees around its perpendicular axis and deformed in the die. Finally, the deformed sheet which was grooved in the previous step is located in the flat die, and the same strain is applied uniformly to the whole portion of the sheet. According to equation (1) and the geometry of figure 1, shear strain at each step is \( \tan \theta \), so the equivalent strain for each step is obtained from equation (2), which is 0.58 and the effective strain after the first cycle is 1.16.

\[
\gamma_{xy} = \frac{\Delta x}{t} = \tan \theta \tag{1}
\]

\[
\varepsilon_{eff} = \sqrt{\frac{\gamma_{xy}}{3}} \tag{2}
\]

This process has been used successfully in producing various ultrafine-grained sheets of aluminum alloys \[20, 22–24\], copper alloys \[21, 25\], Cu–Zn alloys \[26–28\], low carbon steel \[29, 30\], and pure nickel sheets \[31–33\]. Most of the studies mentioned above have investigated the effects of pass numbers on general microstructural and mechanical evolution, and some used the FEM method for analyzing stress and strain distribution on the material during the process. However, a few researches study the variations in fracture behavior or elastic and plastic properties of the processed materials such as elastic modulus and anisotropic plastic ratios, which can be useful in better recognition of the behavior of the material after the processes \[34, 35\]. These parameters could be useful in different areas. These data can used for better introduction of the properties of materials in FEM simulation of processes. Also, in some cases such as deep drawing, the calculation of anisotropic parameters is useful for the prediction of spring back, which is caused by high inserted strain after initial processes such as rolling or CGP \[36\].

Moreover, the accuracy in tracking the variation of the material parameters such as elastic modulus after performing the SPD processes can play a role in the design structure. On the other hand, CGP is also one of the processes in which higher amounts of the shear strains highly influence the material during the deformation. Hence, the prediction of its behavior, such as anisotropy, can be beneficial for controlling different forming parameters.

Digital image correlation (DIC) is one of the non-contact methods for investigation and calculating the elastic and plastic behavior. DIC can be considered as one of the newest and most precise methods for measuring deformation and strain field in the materials \[37\]. Considering the fact that the DIC method can measure the
transverse strain continuously during the tensile test with a notable resolution, it is a suitable way for studying the variation of different factors in materials such as anisotropy, Poisson’s ratio, and so forth. Due to these outstanding abilities, the DIC method was used frequently for measuring the transverse strain in recent years rather than other techniques such as strain-gauge and interferometric methods [38–40]. So the limitation in these methods, such as sensitivity to temperature, high pressure, and bending, is prevented in the DIC method [41, 42]. Rahmatabadi et al. [43] obtained anisotropy coefficients in multi-layered Al/Brass composite produced by ARB from strain values in two lengths and width directions via the DIC technique. In another study, they used the DIC method for investigation of the behavior of Al 1050 strips fabricated by the ARB process [37]. Sanchez et al.[44] implemented the DIC method for accurate and convenient identification of the elastic and plastic properties in shape memory alloys. Kumer et al. [45] studied the effects of the geometrical variation of the CGP processed specimen on the results of the tensile test using the FEM analysis and implemented the DIC technique for validation of their FEM results.

On the other hand, one of the critical parameters, which are considered recently in studying the behavior of the materials after SPD processes are fracture toughness. It has been reported that different SPD techniques can cause a distinct trend in rising or falling the fracture toughness of various materials after the processes. Hohenwarter et al.[46] reported the increase in fracture toughness of Ni after processing by HPT. Sabirov et al.[47] showed that the ultrafine-grained commercially pure titanium processed ECAP had lower fracture toughness compared to initial samples after the first cycle of the process. In another study, it was reported that after the first cycle of ECAP on Al 7075, the fracture toughness decreases, but by further performing the process in the fourth cycle, the fracture toughness was higher than the initial sample [48]. Mohammadi et al.[49] showed a decrease in the values of fracture toughness by increasing the number of CGP cycles on pure copper. So, studying the effects of different cycles of the CGP process on the fracture toughness of the materials seems essential.

Accordingly, in this paper, the brass sheets were processed by the CGP process at room temperature and 200 °C. Initially, the microstructural evolution and general mechanical properties, such as microhardness of the sheets, were investigated. Then using the tensile test and DIC method elastic and plastic properties, CGP processed sheets were specified. Anisotropy coefficient was obtained from longitudinal and transverse measured strains during the uniaxial tensile test at all three directions of 0°, 45° and 90° for the specimens. Furthermore, the effect of the CGP process in different cycles on the plane stress fracture toughness of the brass sheet was evaluated for the first time. Also, the effect of temperature was shown in mechanical and microstructure properties, anisotropy, and fracture toughness.

2. Material preparation and methodology

The brass alloy with the chemical composition as listed in table 1 was used in this research. The samples with a thickness of 3 mm, 40 mm width, and 56 mm length were cut from the as-received material. The samples were deformed by the CGP process, which its die with groove, and flat sections were produced from hot-worked tool steel, and its hardness was 56 HRC. The used die and equipment are shown in figure 2. The process was conducted using a hydraulic press at a ram speed of about 5 mm min⁻¹ at room temperature and a temperature of 200 °C. The sample at room temperature was processed up the second cycle and at the temperature of 200 °C in 2.5 cycles. In order to study the evolution of microstructure, the transverse cross-section of specimens became a mirror-like state by polishing, and then samples were etched. Microstructural changes of the specimens were investigated by optical microscopy (OM). Also, SEM micrographs were used to investigate the variation of fractured surfaces of the samples before and after the process.

The hardness measurement after mounting and polishing of the samples was carried out using a Vickers microhardness machine-Copa under a force of 50 g, which was applied at a period of 20 s. Hardness was measured in two different regions of the samples, the surface, and the interior zone in the depth of 1.5 mm from surface.

Furthermore, digital image correlation (DIC) has been utilized to identify mechanical properties (elastic and plastic properties) of CGP-ed sheets. Three different tensile specimens were prepared for each state from the different unprocessed and processed samples, according to the ASTM E8. The strain rate in the tensile test, carrying out at room temperature, was 0.5 mm min⁻¹; the test was conducted by a Santam tensile machine.

| Table 1. Chemical composition of brass. |
|----------------------------------------|
| Element | Cu | Zn | Pb | Fe | Sn |
| Mass % Bal. | 35.96 | 3.1 | 0.19 | 0.3 |

...
equipped with the DIC instruments. As shown in figure 3(a), the samples were initially coated by the thin white layer with a randomly distributed black spot. Then, the test was carried out for each state. To better derive the anisotropy properties of the CGP processed specimen, the uniaxial tensile test was carried out in three directions of 0°, 45° and 90° for each specimen. The term anisotropy refers to the ratio of transverse strain to strain in the direction of the sample thickness. As shown in figure 3(b), the 2D DIC equipment was utilized for capturing the images. So, determining in-plane strains can be possible. For each level, 60 images were captured in one minute, and the images were analyzed using the DIC software, and the displacement parameter, which is used for calculating strain variation, was achieved.

For further investigation of the behavior of the brass sheets after the CGP process, plane stress fracture toughness parameters were calculated for the initial and CGP processed sheets. The experiments were conducted by providing test specimens and instruments and obtaining R-curves according to the ASTM-E561[50]. The experimental instrument and prepared sample for testing is shown in figure 4. It is necessary to mention that the generated cracks in all the specimens are identical. By loading based on the first mode of the fracture, the test was conducted at a rate of 0.5 mm min⁻¹, and fracture toughness of the specimens before and after the CGP process was achieved and compared.

To validate the strain measured by the DIC setup, a smart but simple experiment is used. For this aim, the strain value in a specified distance of cantilever beam was measured by DIC and Strain Gauge Data Logger. Strain values measured using these two methods were less than 6%. Strains’ values in different loading conditions have been compared in both used methods, as shown in the following table (Table 2).
3. Results

The CGP process was conducted successfully for two cycles in the brass sheets at room temperature. By further processing the material at room temperature, the cracks were emerged in the specimen and made the processing impossible. So, for further processing of the sample and also the investigation of the effects of the temperature rise, the process was also conducted at 200 °C and the specimen was successfully processed for two and a half cycles.

3.1. Microstructure observation

The optical microscopy images of as-received and CGP processed brass sheets after different processing conditions are depicted in figure 5. As shown in figure 5(a) for the as-received brass, the typical structure for the brass with α phase matrix embedded β second phase is shown in the micrograph [51, 52]. The average grain size of the sample is about 450 ± 100 μm. By further processing after one and two cycles, the grain size becomes finer and reached the average grain size of 200 ± 70 and 100 ± 50 μm, respectively. It is worth noting that a few twins which are observed in the first cycle of the CGPed sample are gradually disappeared by increasing the cycle number to the second pressing cycle [53]. As shown in figure 5(d), for the two and a half cycle processed sample at 200 °C the grain size is a bit larger due to the effects of temperature. Moreover, β phases were broken into smaller particles and distributed in the structure. Usually in most SPD processes, due to the lack of uniform strain distribution, the microstructure distribution is not uniform and is so-called inhomogeneity. The inhomogeneity in the network even after the second cycle is seen due to non-uniform insertion of strain during the CGP process. This issue was previously shown by FEM analysis in different studies [54].

3.2. Microhardness

Figure 6 shows the microhardness values of brass sheets before and after the different cycles of the CGP process. The hardness values were measured in two different regions of the surface and interior zone of the sample to investigate the variation as can be seen in the curves; by processing the sample in more cycles, the hardness value increases. This increase in hardness is more evident after the first cycle of the process than the other cycles. Furthermore, the hardness value for processing of the sample in two and a half cycles at 200 °C is shown in the

| Load values (kg) | Strain values using strain gauge (mm mm⁻¹) | Strain values using DIC (mm mm⁻¹) | Percentage error (%) |
|-----------------|------------------------------------------|---------------------------------|----------------------|
| 5               | 93                                       | 95                              | 2                    |
| 10              | 232                                      | 241                             | 4                    |
| 20              | 508                                      | 500                             | 1                    |
| 30              | 800                                      | 842                             | 5                    |
| 40              | 1143                                     | 1126                            | −1                   |
As it is clear, the results for two and a half cycle processed sample at 200 °C is lower than the two-cycle processed sample at room temperature. This is due to the effects of temperature and attributed to the variation of microstructure and also the dislocation densities at a higher temperature, which was previously shown by other researchers [55]. The hardness of the sample after two and a half cycles process at 200 °C is almost the same as the one-cycle processed sample at room temperature. Moreover, as shown, the hardness value at the surface of the samples after the process is higher than the interior region. For example, the hardness after the first cycle in the surface is 162 Hv, whereas, in the interior region, the value is 135 Hv. This shows more than 20% variation in the hardness of the sample along the thickness. This variation is attributed to the nature of the CGP process, which applies non-uniform strains along the thickness of the sample [26, 56]. Also, it was shown that the equivalent

**Figure 5.** The OM micrograph of the brass sheet for (a) as received; (b) first, (c) the second cycle of the CGP process at room temperature, and (d) two and a half cycle process at 200 °C.

**Figure 6.** Microhardness value for the initial and CGP processed brass in different conditions at two distinct zones: interior zone and Surface.
strain in the surface of the sample is more than the interior region. Mou et al. [54] showed that the equivalent strain after the second cycle of the CGP process at the surface was between 0.43 and 1.13. For the interior region, they showed a range of 0.34–0.94. Also, this issue was previously demonstrated in the CGP processing of different materials [56]. On the other hand, by processing the sample at the second cycle, the variation in the hardness value between the surface and interior region reaches 16%. This shows that by further processing the sample, the homogeneity in strain and subsequently in hardness value increases.

3.3. Mechanical properties

The engineering stress–strain curves for the initial brass sheet and CGP processed ones are depicted in figure 7. As it is shown, after performing the first cycle of the process at room temperature, the strength increases dramatically. The trend for elongation is vice versa, and it decreases. For the initial brass sample, the ultimate strength and elongation are 303 MPa and 78%, respectively. After performing the first cycle, the ultimate strength reaches 384 MPa, and the elongation drops to the value of 4.4%. By conducting the second cycle of the process at room temperature, the ultimate strength further increases to the value of 458 MPa. Moreover, the elongation increases rather than the one-cycle processed sample to 7%. However, this value is much less than the initial elongation. Due to the effects of temperature in processing, the strength of two and a half cycles CGP processed sample at 200 °C is a little less than the two cycles processed sample at room temperature. However, the elongation is higher in two and a half cycles processed sample at 200 °C. The reasons for the variation of the mechanical properties in the alloy can be described by the role of strain hardening, dislocation densities, grain refinement, and grain boundaries [22, 29]. Generated and existed dislocation in the material are blocked behind the grain boundaries and act as the pinning effects. Therefore, an improvement in tensile strength and reduction in ductility was observed after the first cycle of the process by strain hardening. However, as it is seen after performing the second cycle of the process, the elongation is as like as strength increases. This increase can be justified in such a way that after the second cycle, more equiaxed grains were created, and their effects are more than strain hardening. Furthermore, a bimodal structure is seen in the processed alloys, which was also shown in the reference of [35]. The combination of coarse and fine grains leads to an increase in the elongation. Finer grains act as obstacles for dislocation movement, and subsequently, the strength improves. Whereas, coarser grains act as the agents in the slip of dislocations and therefore, elongation increases. The same results were observed in ECAP processing of brass alloy after three cycles [57]. Furthermore, the higher elongation and lower strength of two and a half cycle processed sample at 200 °C rather than the two cycles processed sample at room temperature returns to the effects of temperature and its influences on microstructure. At higher temperatures due to the dynamic recovery, dislocations are moved easily, and the grain can grow rather than processing at room temperature, which leads to these properties [27].

Elongation dramatically decreases by first cycle of the CGP process, and after the first cycle, the elongation, slightly increases with decreasing grain size. According to some articles in prestigious journals, in fact, improvement of the poor ductility in higher cycles could be the result of the bimodal distribution microstructure of micro- and nano-grains and combining nano-scale twins in the UFG microstructure [27].
3.4. Elastic and plastic parameters

DIC method was used for accurate estimation of the elastic and plastic parameters before and after the CGP process on brass sheets. By obtaining the displacements in the material, the strain values were specified along the length and width of each test specimen. As an example, the contours, which are indicative of longitudinal strain distribution in the gauge length of the tensile specimen in various loading levels after the first cycle of the CGP process on the brass sheet is depicted in figure 8. As it is apparent in the contours, by increasing the force during the tensile test, the strain in the tensile test specimen increases, and the fracture occurs in the place with higher strain concentration.

After obtaining the strain in different directions of the sample and tracking the change in the obtained images, and deriving the force value from the tensile test, the different elastic and plastic parameters were achieved. In the elastic region, the different material parameters such as Young modulus, Poisson’s ratio, and the exact values of yield stress were obtained. These parameters are presented in table 3. As shown for the yield stress, the unprocessed sample has a yield stress of 105.6 MPa. By performing the process, the yield stress of the sample after the first cycle reaches 344.7 MPa. More than three times, the increase in yield strength value is shown after the first cycle. By processing the sheet in the second cycle, the yield stress reached 437.6 MPa. However, as it is seen for the two and a half cycles processed sample at 200 °C, the yield stress in a little lower than the two- cycles processed sample at room temperature. But it is more times higher than the strength of the initial sample. By comparison of the obtained results for the elastic modulus and Poisson’s ratio, it can observe that these ratios have slight changes than the initial values. Elastic modulus, after performing the second cycle the process increases about 6%, which can attribute to the insertion of higher amounts of strain during the process, which causes a little variation in atomic network parameters. Furthermore, grain refinement after the CGP process is affected in the variation of these parameters. The elastic modulus for the two and a half cycles processed sample at 200 °C is lower than the two- cycle processed sample at room temperature. The increase in the elastic modulus of the material after the SPD techniques were observed by different researchers [43, 58]. By comparing the Poisson’s ratios, it is seen that this ratio in the CGP processed samples increases by increasing the cycle numbers. However, all obtained Poisson’s ratios after the process are lower than the ratio of the initial sample. The Poisson’s ratio after the first and second cycle of the process at room temperature decreases about 7 and 3%, respectively. The reduction for the two and a half cycles processed sample at 200 °C is about 2%.

![Figure 8](image.png)

**Figure 8.** The longitudinal strain distribution in various loading condition after the first cycle of the CGP process.

| Number of CGP Pass | Yield strength (MPa) | Elastic modulus (GPa) | Poisson ratio (%) |
|--------------------|----------------------|-----------------------|------------------|
| 0                  | 105.63 ± 1.2         | 99.7 ± 0.2            | 0.331            |
| 1 cycle-RT         | 344.7 ± 3.2          | 102.6 ± 0.1           | 0.306            |
| 2 cycle-RT         | 437.61 ± 4.7         | 105.7 ± 0.2           | 0.319            |
| 2.5 cycle-200 °C   | 435.01 ± 5.1         | 104.6 ± 1.2           | 0.323            |

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Table 4. The plastic parameters calculated by DIC parameters measured by DIC for the initial and CGP processed brass sheets.

| Number of CGP cycle | Strength coefficient (MPa) | Ultimate tensile strength (MPa) | Strain hardening index | Anisotropy coefficient | Elongation (%) |
|---------------------|-----------------------------|---------------------------------|------------------------|-----------------------|---------------|
| 0                   | 259.3                       | 304.95 ± 1.50                   | 0.2631                 | 0.298                 | 76.82 ± 0.82  |
| 1 cycle             | 356.1                       | 384.95 ± 7.11                   | 0.0698                 | 0.565                 | 4.48 ± 0.61   |
| 2 cycle             | 428.6                       | 458.92 ± 5.20                   | 0.0567                 | 0.543                 | 7.06 ± 1.2    |
| 2.5 cycle 200 °C    | 426.8                       | 447.5 ± 3.7                     | 0.0321                 | 0.496                 | 12.54 ± 0.9   |

The obtained plastic properties of the samples before and after the CGP process from the DIC method are presented in Table 4. These parameters include strength coefficient, ultimate tensile strength, strain hardening index, anisotropy coefficient, and elongation. The UTS and elongation parameters were discussed in the previous section. As it is clear from the results of the strength coefficient, this parameter is intensely affected by the tensile strengths and increases by increasing the cycles of the process. Another critical parameter in the investigation of the plastic behavior of the samples is the strain hardening index. This parameter is indicative of the strengthening of a metal by plastic deformation and determines the volume of workability. The material with a higher index is appropriate for processing at lower temperatures. Furthermore, it was reported that higher amounts of strain cause a reduction in the value of this index [37]. By performing the CGP process on brass sheets, this strain hardening index decreases significantly, and as mentioned, the main reason for this significant decrease is applying a higher amount of strain during the process to the material.

On the other hand, one of the significant difficulties since the invention of different SPD techniques is achieving microstructure with a higher amount of grain homogeneity. This inhomogeneity shows itself further in SPD processing of the sheets. The reasons for this inhomogeneity are the insertion of non-uniform strain due to the nature of the processes, the effects of frictional forces, and some defects in the materials. These problems cause strain gradient in the processed sheet, which leads to the anisotropy in them. So, investigation of this parameter seems necessary in SPD processing of the materials and especially sheets. So, the parameter in this study was calculated by the DIC method. For proper measuring the anisotropy ratio, the tensile test was carried out in three different directions of 0°, 45°, and 90° of the processed sheets. The parameter is defined by subdividing the plastic strain in width to the strain of thickness. As is seen in Table 4, the anisotropy coefficient after the first cycle of the CGP process is increased rather than the initial state. By performing the second cycle of the process, this ratio is slightly decreased rather than one cycle processed sample. However, the value is much more than the initial sample. For the sample processed in two and a half cycles at 200 °C, the coefficient is smaller than the amount of one cycle and two cycles processed sample at room temperature. The reason for this difference is the change or growing the grain shapes and sizes at higher temperatures rather than the lower ones.

As one of the investigated cases, the stress-strain curve at three directions of 0°, 45° and 90° after the first cycle of the CGP process and obtained anisotropy curve in different strains for the initial sample and the test specimen at each direction are depicted in Figure 9. As it is illustrated in Figure 9(a), the test specimens at different directions show distinct behavior, which further shows the anisotropy behavior in the processed sheets. The specimen in the direction of 0° shows two times more elongation than the specimen in the direction of 45°. According to Figure 9(b) for the as-received material, the coefficient initially increases and then decreases. This trend is similar for the sample after the first cycle in the direction of 45°. In the test specimen at the directions of 0° and 90°, the initial drop in coefficient followed by the increase at medium strains and again reduction at higher strains are seen. The reason for these changes is the variation in crystalline defects, dislocation densities, and different strain distribution along the thickness in various directions.

3.5. Fracture toughness

The variation of maximum force ($P_{\text{max}}$) during the fracture test for the initial brass sample and CGP processed samples is depicted in Figure 10. $P_{\text{max}}$ is indicative of the material resistance to crack initiation and is one of the elastic parameters. The results show the increase in the values of $P_{\text{max}}$ after performing the CGP process in the samples. This means that CGP processed samples need higher forces for initiation of crack development.

The result of two and a half cycle processed samples at 200 °C is similar to most other properties and is lower than the two-cycle processed sample at room temperature. But this is higher than one cycle processed sample and initial sheets. The variation trend in values of $P_{\text{max}}$ is similar to the changes in the ultimate strength after the CGP process. Similar trends were seen after CGP processing of copper or Al-Mn sheets by CGP [49, 59]. Grain refinement and strain hardening are the main reason for the increase of the crack initiation forces. The representation of the undeformed and deformed crack specimen with pre-crack after the first mode of fracture for the one cycle CGP processed sheet at different time intervals is depicted in Figure 11. As it is shown, by reaching the force to the maximum value, the crack initiated to grow and, after that, immediately extended in a
line until full rupture. After performing the test and recording the crack growth in various forces, the plane stress fracture toughness ($K_C$) of the samples was specified [60]. The $K_C$ is achieved from the tangency of $R$-curves and applied $K$-curves of the samples. $R$-curves are the incessant tracking of $K_R$ (the crack grows resistance) versus crack development in the sample. It is specified by the experimental test from the beginning of the crack up to its uneven development by the recorded force values of each crack length.

On the other hand, The $K$-curves are achieved by constant load and growing extents of crack length based on the equations [49]. As one of the cases, the $R$ curve of the first cycle processed brass sheet is shown in figure 12 and $K_r$ and $K$ curves and obtained $K_c$ value is depicted in the figure. The obtained results of $K_c$ for the initial

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**Figure 9.** (a) Stress-strain curves and (b) the variation of anisotropy coefficient for the as-received and processed brass sheets in different directions after the first cycle of the CGP process.

**Figure 10.** The variation of $P_{max}$ from the fracture test for different CGP cycles.
sample and CGP processed samples after different cycles and condition is depicted in figure 13. It is obvious that by increasing the number of the CGP cycled, the fracture toughness of the brass sheets increases. The obtained $K_c$ for the initial sample is 38.3 MPa.m$^{1/2}$. After the second cycle of the process, which was performed at room temperature, the $K_c$ increased to 52.3 MPa.m$^{1/2}$. For two and a half cycle processed sample at 200 °C, the $K_c$ reaches 54.8. The $K_c$ parameter is thoroughly affected by the variation of the strength and elongation, and due to an increase in these parameters after the CGP test, the $K_c$ values increase rather than the initial sample [50].
3.6. Fracture morphology

In figure 14, the morphology of the fracture surface of the tensile specimen for the initial sample and after the different conditions of applying the CGP process on brass sheets is illustrated. As it can be observed, in the initial sample, the higher ductility of the specimen and subsequently, soft fracture behavior leads to the fracture surface, which consists of deep dimples. The fracture in this specimen is caused by beginning, development, and a combination of microvoids. It showed rounded tips, which is caused by higher amounts of plasticity in the ductile metals. It is important to note that the geometry of the dimples is indicative of the type of loading in the specimen through the test, and their orientation is indicative of the direction in which cracks grow [61]. As it is shown in figure 14(b), after performing the first cycle of the CGP process, strain inhomogeneity during the process, which can be the representative of shear overloads, caused the ordering of dimples non-uniform, and the dimples are smaller and elongated. Furthermore, a gray, fibrous surface, which is indicative of the ductile fracture, is seen in surfaces [62]. Nonetheless, as is shown in figure 14(c), after the second cycle of the CGP, because of the more uniform strain distribution than the first cycle, the dimples become slightly equiaxed in many directions of the fracture surface. These small and elongated dimples are the representative of the shear

Figure 13. The changes of plane stress fracture toughness for unprocessed and CGP processed brass sheets.

Figure 14. SEM images of the fracture surface of (a) unprocessed, (b) after the first cycle (c) after the second cycle (d) after the second pass at 200 °C.
ductile fracture. The two and half cycles processed sample at 200 °C also shows the shear ductile fracture. As shown in figure 14(d), small and relatively elongated dimples are seen in fracture surface of this specimen.

4. Conclusion

Constrained groove pressing was successfully conducted in two consecutive cycles at room temperature, and then a half cycles at a temperature of 200 °C on brass sheets, and the microstructural and mechanical and fracture behavior of the processed samples were examined. For the first time, the variation of elastic and plastic behavior such as elastic modulus, strain hardening index, anisotropy coefficient in the CGP processed sheets was calculated using the DIC technique. The following results can be driven:

Optical microscopy images show the reduction in the grain size of the brass sheets after performing the CGP process.

It was determined that by increasing the cycle of the CGP process, the ultimate and yield strengths of the processed sheets increase. The ultimate tensile strength of the sample after two passes of processing at room temperature reached 458 MPa. After two and a half passes of CGP at 200 °C, the ultimate tensile strength reached 447 MPa. However, the elongation decreased dramatically rather than the initial state. It dropped from 76 to 7% after the second pass of processing at room temperature.

By further processing the samples in higher passes, the elastic modulus and Poisson’s ratios of the sheets show a slight variation. The elastic modulus changed from to initial value of 99.7 GPa to the value of 105.7 for the two cycles processed sample. For two and a half cycles processed sample, it was 104.6. The Poisson’s ratios of the processed sample were a little less than the initial values.

Strain hardening index after the CGP process experienced a sharp decrease in comparison to the initial state. After two cycles of the process at room temperature, it was 0.0567 rather than the initial state of 0.2631. After two and a half cycles of processing at 200 °C, the index was 0.0321. The influential factors in these reductions are cold working and grain refinement.

By performing the CGP process, the anisotropy coefficient increased. However, the number of CGP cycles reduces the anisotropy ratio. Changes of the fracture toughness in CGP processed samples are analogous to other studies and increased with improving the strength of the material after the process.

SEM investigation of the fracture surfaces after the CGP process and its comparison with the initial sample indicate shearing ductile rupture mode in the processed samples rather than ductile mode due to appearing of small and elongated dimples.

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References

[1] Ferrasse S et al 2008 Scale up and application of equal-channel angular extrusion for the electronics and aerospace industries Materials Science and Engineering: A 493 130–40
[2] Zhilyaev A et al 2005 Microstructural evolution in commercial purity aluminium during high-pressure torsion Materials Science and Engineering: A 410 277–80
[3] Yu C et al 2010 The processing of pure titanium through multiple passes of ECAP at room temperature Materials Science and Engineering: A 527 6335–9
[4] Hadizadeh A et al 2011 Influence of grain size and texture on Hall–Petch relationship for a magnesium alloy Scr. Mater. 65 994–7
[5] Yuan W et al 2011 Microstructural evolution in magnesium alloy AZ31 during cyclic extrusion compression Materials Science and Engineering: A 65 994–7
[6] Samadpour F, Faraji G and Siasarsani A 2014 Processing of AM60 magnesium alloy by hydrostatic cyclic expansion extrusion at elevated temperature as a new SPD method Int. J. Miner. Metall. Mater. 0–0
[7] Verlinden B 2018 Severe plastic deformation of metals Metallurgical and Materials Engineering 165–82 https://doi.org/10.30544/380
[8] Samadpour F et al 2019 Experimental and finite element analyses of the hydrostatic cyclic expansion extrusion (HCEE) process with back-pressure Journal of Ultrahigh Grained and Nanostructured Materials 52 25–31
[9] Shariq F et al 2016 Effect of ECAP temperature on microstructure and mechanical properties of Al–Zn–Mg–Cu alloy Progress in Natural Science: Materials International 26 182–91
[10] Zhao X et al 2010 The processing of pure titanium through multiple passes of ECAP at room temperature Materials Science and Engineering: A 527 6335–9
[11] Richert M, Liu Q and Hansen N 1999 Microstructural evolution over a large strain range in aluminium deformed by cyclic-extrusion–compression Materials Science and Engineering: A 260 275–83
[12] Chen Y et al 2008 Microstructure evolution in magnesium alloy AZ31 during cyclic extrusion compression J. Alloys Compd. 462 192–200
[13] IOP Publishing Mater. Res. Express 7 (2020) 116526 A Shahmirzaloo et al

13
[12] Vorhauer A and Pippan R 2004 On the homogeneity of deformation by high pressure torsion Scr. Mater. 51 921–5

[13] Rahmatadbadi D and Hashemi R 2017 Experimental evaluation of forming limit diagram and mechanical properties of nano-/ultra-fine grained aluminum strips fabricated by accumulative roll bonding Int. J. Mater. Res. 108 1036–44

[14] Rahmatadbadi D et al 2018 Fracture toughness investigation of Al1050/Cu/MgAZ31ZB multi-layered composite produced by accumulative roll bonding process Materials Science and Engineering: A 734 427–36

[15] Gupta A K, Maddukuri T S and Singh S K 2016 Constrained groove pressing for sheet metal processing Prog. Mater. Sci. 84 403–62

[16] Pouraliakbar H, Jandaghi M R and Khalaj G 2017 Constrained groove pressing and subsequent annealing of Al-Mn-Si alloy: microstructure evolutions, crystallographic transformations, mechanical properties, electrical conductivity and corrosion resistance Mater. Des. 124 34–46

[17] Rahmatadbadi D et al 2017 Experimental evaluation of the plane stress fracture toughness for ultra-fine grained aluminum specimens prepared by accumulative roll bonding process Materials Science and Engineering: A 708 301–10

[18] Lee J and Park J 2002 Numerical and experimental investigations of constrained groove pressing and rolling for grain refinement J. Mater. Process. Technol. 130 208–13

[19] Park J-J and Park N-J 2005 Influence of orthogonal shear on texture and R value in aluminium sheet J. Mater. Process. Technol. 169 299–307

[20] Krishnaiah A, Chakkingal U and Venugopal P 2005 Production of ultrafine grain sizes in aluminium sheets by severe plastic deformation using the technique of groove pressing Scr. Mater. 52 1229–33

[21] Krishnaiah A, Chakkingal U and Venugopal P 2005 Applicability of the groove pressing technique for grain refinement in commercial purity copper Materials Science and Engineering: A 410 337–40

[22] Shin D H et al 2002 Constrained groove pressing and its application to grain refinement of aluminum Materials Science and Engineering: A 328 98–103

[23] Zirkle J et al 2009 Ultrafine-grained structure development and deformation behavior of aluminum processed by constrained groove pressing Materials Science and Engineering: A 503 126–9

[24] Hosseini E and Kazeminezhad M 2009 Retracted: Nanostructure and Mechanical Properties of 0–7 Strained Aluminum by CGP: XRD, TEM and Tensile Test (Amsterdam: Elsevier)

[25] Hosseini E et al 2009 On the evolution of flow stress during constrained groove pressing of pure copper sheet Comput. Mater. Sci. 45 855–9

[26] Peng K et al 2011 Equivalent strain, microstructure and hardness of H62 brass deformed by constrained groove pressing Comput. Mater. Sci. 50 1526–32

[27] Peng K et al 2007 Grain refinement and crack prevention in constrained groove pressing of two-phase Cu–Zn alloys Scr. Mater. 56 987–90

[28] Peng K et al 2009 Microstructure dependence of a Cu–38Zn alloy on processing conditions of constrained groove pressing Acta Mater. 57 5543–53

[29] Khodabakhshi F, Kazeminezhad M and Kokabi A 2010 Constrained groove pressing of low carbon steel: nano-structure and mechanical properties Materials Science and Engineering: A 527 4043–9

[30] Shahmirzaloo A et al 2018 Interface sheet-constrained groove pressing as a modified severe plastic deformation process Mater. Sci. Technol. 34 1669–78

[31] Kumar S and Raghuv T 2011 Tensile strength and strain hardening characteristics of constrained groove pressed nickel sheets Mater. Des. 32 6550–7

[32] Kumar S and Raghuv T 2010 Processing and characterization of pure nickel sheets by constrained groove pressing (CGP) technique Mater. Sci. Forum ed J T Wang, R B Figueiredo and T G Langdon 667-669

[33] Kumar S and Raghuv T 2013 Mechanical behaviour and microstructural evolution of constrained groove pressed nickel sheets J. Mater. Process. Technol. 213 214–20

[34] Yadav P C et al 2016 Microstructural Inhomogeneity in Constrained Groove Pressed Cu–Zn alloy Sheet 25 2604–14

[35] Yadav P C et al 2019 Influence of Short Heat-Treatment on Microstructural and Mechanical Inhomogeneity of Constrained Groove Pressed Cu–Zn Alloy 238 121912

[36] Zein H, El Sherbiny M and Abd–Rabou M 2014 Thinning and spring back prediction of sheet metal in the deep drawing process Mater. Des. 53 797–808

[37] Rahmatadbadi D et al 2019 Using digital image correlation for characterizing the elastic and plastic parameters of ultrafine-grained Al 1050 strips fabricated via accumulative roll bonding process Mater. Res. Exp. 6 086542

[38] Madadi A et al 2018 Digital image correlation to analyse the flexural behavior of lightweight ferrocement slab panels Constr. Build. Mater. 189 967–77

[39] Mehdiyazhi M et al 2018 Multi-scale digital image correlation for detection and quantification of matrix cracks in carbon fiber composite laminates in the absence and presence of voids controlled by the cure cycle Composites Part B: Engineering 154 138–47

[40] Segouin V et al 2019 Mechanics-aided digital image correlation for the investigation of piezoelectric and ferroelectric behaviour of a soft PZT J. Eur. Ceram. Soc. (https://doi.org/10.1016/j.jeurceramsoc.2018.12.036)

[41] Lawrence C et al 1999 A fibre optic sensor for transverse strain measurement Exp. Mech. 39 202–9

[42] Liu Y, Zhang L and Bennion I 1999 Fibre optic load sensors with high transverse strain sensitivity based on long-period gratings in B/ Ge co-doped fibre Electron. Lett. 35 661–3

[43] Rahmatadbadi D et al 2019 Characterizing the elastic and plastic properties of the multilayered Al/Brass composite produced by ARB using DIC Materials Science and Engineering: A 753 70–8

[44] Sánchez-Arévalo F and Pulos G 2008 Use of digital image correlation to determine the mechanical behavior of materials Mater. Charact. 59 1572–9

[45] Kumar S et al 2019 Influence of Inhomogeneous Deformation on Tensile Behavior of Sheets Processed through Constrained Groove Pressing Journal of Engineering Materials and Technology 141 041007

[46] Hohenwarter A and Pippan R 2011 Fracture toughness evaluation of ultrafine-grained nickel Scr. Mater. 64 982–5

[47] Sabirov I et al 2010 Effect of equal channel angular pressing on the fracture behavior of commercially pure titanium Metallurgical and Materials Transactions A 41 727–33

[48] Darban H,Mohammadi B and Djavanroodi F 2016 Effect of equal channel angular pressing on fracture toughness of Al-7075 Eng. Fail. Anal. 65 1–10

[49] Mohammadi B, Tavoli M and Djavanroodi F 2014 Effects of constrained groove pressing (CGP) on the plane stress fracture toughness of pure copper Struct. Eng. Mech. 52 957–69
[50] Rahmatabadi D et al 2018 Evaluation of fracture toughness and rupture energy absorption capacity of as-rolled LZ71 and LZ91 Mg alloy sheet Mater. Res. Express 6 036517

[51] Tarasov S Y et al 2018 Microstructure and tensile properties of Cu–Zn brass after severe plastic deformation AIP Conf. Proc. (AIP Publishing LLC)

[52] Matsumoto J, Anada H and Furui M 2007 The effect of grain size and amount of β phase on the properties of back-torsion working in 60/40 brass Advanced Materials Research 15–17 ed T Chandra, K Tsuzaki, M Militzer and C Ravindran 15–17 (Switzerland: Trans Tech Publications) 661–6

[53] Ebrahimi M et al 2014 Wear properties of brass samples subjected to constrained groove pressing process Mater. Des. 63 531–7

[54] Mou X et al 2011 The influence of the equivalent strain on the microstructure and hardness of H62 brass subjected to multi-cycle constrained groove pressing J. Mater. Process. Technol. 211 590–6

[55] Goodarzy M et al 2014 The effects of room temperature ECAP and subsequent aging on mechanical properties of 2024 Al alloy J. Alloys Compd. 585 753–9

[56] Sajadi A, Ebrahimi M and Djavanroodi F 2012 Experimental and numerical investigation of Al properties fabricated by CGP process Materials Science and Engineering A: 552 97–103

[57] Mousavi S E, Meratian M and Rezaeian A 2017 Investigation of mechanical properties and fracture surfaces of dual-phase 60–40 brass alloy processed by warm equal-channel angular pressing J. Mater. Sci. 52 8041–51

[58] Mesbah M et al 2016 Nano-mechanical properties and microstructure of UFG brass tubes processed by parallel tubular channel angular pressing Met. Mater. Int. 22 1098–107

[59] Khakbaz F and Kazeminezhad M 2012 Strain rate sensitivity and fracture behavior of severely deformed Al–Mn alloy sheets Materials Science and Engineering A: 532 26–30

[60] Tayyebi M et al 2019 Influence of ARB technique on the microstructural, mechanical and fracture properties of the multilayered Al1050/Al5052 composite reinforced by SiC particles Journal of Materials Research and Technology 8 4287–301

[61] Pasebani S and Toroghinejad M R 2010 Nano-grained 70/30 brass strip produced by accumulative roll-bonding (ARB) process Materials Science and Engineering A: 527 491–7

[62] Callister W D Jr and Rethwisch D G 2012 Fundamentals of Materials Science and Engineering: an Integrated Approach (New York: Wiley)