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# Effect of HPT and CGP Processes on the Copper Mechanical Properties

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**Abstract:** One of the most common methods for production of ultra fine grained materials is severe plastic deformation (SPD). In this study, constrained groove pressing (CGP) and high pressure torsion (HPT) processes as effective methods of severe plastic deformation for the strain imposed on the pure copper were used. This paper presents the results of an experimental research, to review the influence of CGP and HPT processes of the mechanical properties such as hardness and tensile on copper samples has been done. The results of tensile and hardness tests represented that due to applying CGP process, strength and hardness of samples were increased significantly.The results of HPT process showed that hardness in the radial direction is variable and away from disk center in the radial direction continuously increases. Of course, in higher pressing steps the slight decrease in strength and hardness is observed, more explanation is given in this paper. Finally, comparison results of the two methods, their advantages and limitations of them are studied.

**Keywords:** Ultra Fine Grained (UFG), Severe Plastic Deformation (SPD), High Pressure Torsion (HPT), Constrained Groove Pressing (CGP), Mechanical Properties

## 1. Introduction

The grain size of polycrystalline materials plays a major role in dictating many critical properties including the strength and resistance to plastic flow. In general, materials with small grain sizes have several advantages over their coarse-grained counterparts because they have higher strength and other favorable properties including a potential for use in superplastic forming operations at elevated temperatures. Such structures in poly-crystalline materials are known as ultra fine grained. These UFG structures divided into materials having sub micrometer grain sizes where the grains are within the range of 0.1–1 μm and true Nano crystalline materials where the grain sizes are <100nm. It is now established that materials with UFG microstructures may be fabricated using two different approaches which are generally termed the ‘‘bottom-up” and ‘‘top-down” procedures [1].

In the ‘‘bottom-up” procedure, the bulk solids are fabricated through the assembly of individual atoms or nano particulate solids. Examples of this approach include inert gas condensation, electro deposition and ball milling with subsequent consolidation. These approaches have the capability of producing materials with exceptionally small grain sizes but they have some disadvantages because the sizes of the finished products are always very small, there may be some contamination introduced during processing (for example, from the ball milling) and there is invariably at least a low level of residual porosity. The ‘‘top-down” approach avoids the introduction of either contaminants or porosity by taking a bulk solid with a relatively coarse grain size and then processing it to refine the grain size to at least the sub-micrometer levels. There are now several possible procedures for processing these bulk solids but all procedures rely upon the imposition of heavy straining and thus upon the introduc-

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tion of a very high dislocation density. Since these processes introduce SPD into the materials, all of these operations are called SPD processing [2]. Some of these methods are: multidirectional forging (MDF), equal channel angular extrusion (ECAE), HPT, accumulative roll bonding (ARB), repetitive corrugation and straightening (RCS), CGP, constrained grooved rolling (CGR), etc.

Two major SPD processes are HPT and CGP. Regarding the analysis of processes HPT and CGP many researchers have worked that their results are homogeneous strain in the CGP and heterogeneous strain in the HPT, Results are consistent with research done in this article. It should be noted that these researchers to compare these two methods and their advantages and disadvantages have not paid.

## 2. Experimental procedures

### 2.1. CGP

A schematic illustration of a CGP process is presented in Fig. 1. At first, a set of asymmetrically grooved dies tightly constrained by cylinder wall is prepared. As the groove pressing is carried out such that a gap between the upper die and the lower die is the same with the sample thickness, the inclined region of the sample (single hatched area in Fig. 1-b) is subjected to pure shear deformation under plane strain deformation condition. However, no deformation is induced in the flat region (unhatched area in Fig. 1-b). For the present die design with the groove angle (Θ) of 45°, a single pressing yield a shear strain of 1 at deformed region. This is equal to an effective strain ($\varepsilon_{eff}$) of 0.58. The second pressing is performed with a set of flat dies (Fig. 1-c). By flat pressing under the constrained condition, the previous deformed region is subjected to the reverse shear deformation while the previous non-deformed region remains non-deformed.

The cumulative strain ($\varepsilon_{eff}$) in the deformed region following the second pressing becomes 1.16 (double hatched area in Fig. 1-c). After the second pressing, the sample is rotated by 180° (Fig. 1-d). This allows the non-deformed region to be deformed by further pressings due to the asymmetry of the grooved die. Then, the successive pressings with a grooved die (Fig. 1-e) and a flat die (Fig. 1-f) result in a homogeneous effective strain of 1.16 throughout the sample. By repeating a CGP process, a very large amount of plastic strain can be accumulated in the sample without changing its initial dimensions and, as a result, an ultra fine grained structure can be obtained [3]. However, there is a limiting factor in increasing the number of passes. When the number of passes increases, surface micro cracks, gradually appear in the CGP specimens. These micro cracks caused the fracture of CGP sheets in higher pass numbers. It should be noted that this incident is strongly dependent on the materials used. For example, a mentioned fracture in pure Copper happens in the lower pass number than pure aluminum.

Effective strain mentioned in the paragraph above is obtained from the following relations (Eqs. 1-4):

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

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

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

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

By using Eqs. (2), (3) and (4), we obtain Eqs. 5 and 6.

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

$$\varepsilon_{eff} = \frac{\gamma}{\sqrt{3}} \xrightarrow{\gamma=1} \varepsilon_{eff} = 0.58 \quad (6)$$

### 2.2. HPT

As part of this method is under high pressure, the risk of torque is placed so that the severe shear strain is applied to the structure. This strain eventually leads to fine grained in the nano scale. Fig. 3 schematic of the process you see [1]. In the Fig. 3-a part of the side of freedom and can be Ceylon and in cases where the relatively lower pressure is

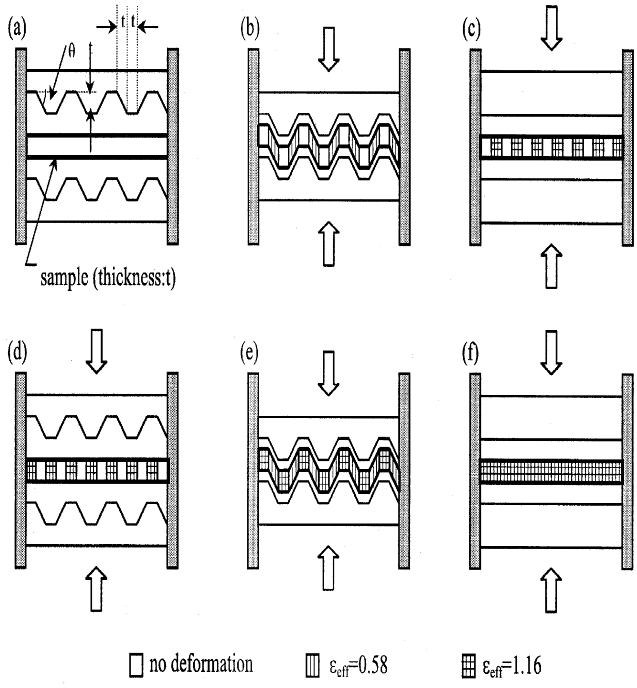


**Fig. 1. A Schematic illustration of the sequences of the constrained groove pressing technique [3].**

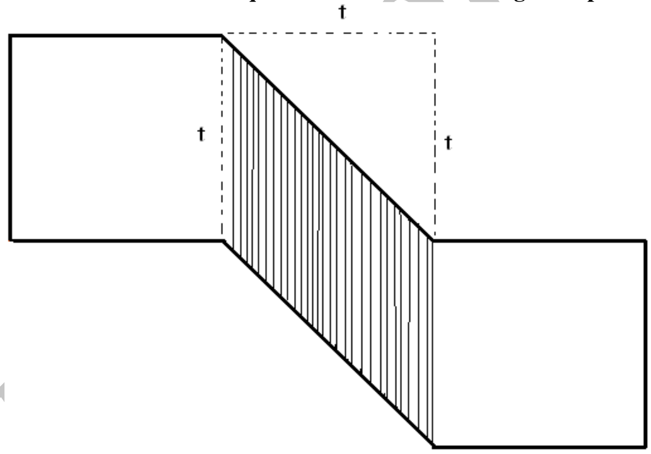

**Fig. 2. The scheme of the deformed region in the sheet under CGP.**

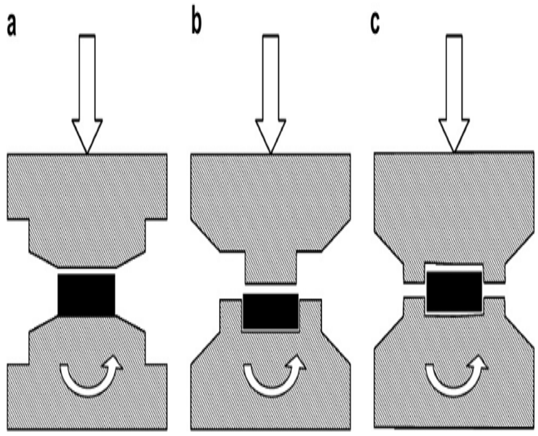


**Fig. 3. The schematic of the pieces between jaws mold**
**a) Free piece, b) piece fully bound, c) piece quasi-bound [1].**

required, can be used. Hydrostatic pressure on this type of themes small piece and the friction between the level formats is the result. When ultra fine grained the piece is considered and the pressure will be numerous, the next two methods are more efficient [2, 4]. In Fig. 3-b piece mandibular cavity located from any direction is bound. Fig. 3-c a piece of semi-bound form has been and during the process, a small piece of metal from the flash format outside seam separation caused. Friction between the flash format and die surface, the hydrostatic pressure necessary has provided [1, 2].

Ultra fine grained in metals, improves the mechanical properties. Hall - Petch related relationship with metal submitted to strength and grain size classification confirms the fact (Eq. 1):

$$\sigma_{y_s} = \sigma_o + k_y d^{-\frac{1}{2}} \qquad (7)$$

In which $\sigma_o$ stress pure shear stress (Stress-slip atomic crystals on the whole), $k_y$ constant yield and d are the grain size. Considering this relation, strength materials obtained by HPT is high range. Because of this process, grain size break into nano scale [4].

Hydrostatic pressure increased in the HPT process until 5 GPa and even in some sources until 7 GPa. According to high pressure, parts manufacturable by HPT method was relatively small due to the nature of the process were rotating. HPT process for producing discs with more situated around size and thickness of 10mm and diameter ring with 1mm or equivalent area is used. Fig. 4 Pieces geometry and applied angle strain and calculated parameters of strain, is shown.

Due to the rotational nature of the process of HPT, imposed strain was not uniform in the radial direction and from the Eq. (2) will follow (Eq. 8) [1]:

$$\gamma(r) = \frac{2\pi nr}{t} \qquad (8)$$

In this regard, t thick pieces, r radial position and n the revolution number is applied to the piece. Due to the non-uniform strain, microstructure and hardness of the final piece, in different places, depending on the radial position is variable.

## 3. Experimental material

In the present study, the sheets of commercial pure copper with the dimensions of 72×52×3 mm were pressed by applying the constrained groove pressing technique described above. Prior to CGP pressing, the as-received sheets were annealed at a temperature of 700 °C for 180 min to obtain a recrystallized structure. Pressing was conducted up to a total of 12 pressings on a 15 ton hydraulic pressing machine operating at a constant press speed of 0.1 mm s−1 at room temperature. For each series of four pressings yields a homogeneous effective strain of 1.16 throughout the sample, 12 pressings are expected to accumulate an effective strain of 3.48.

To investigate the mechanical properties of copper sheets, tensile and hardness tests were carried out on the specimens after each pass of CGP process. The tensile testing specimens were machined such that the gage length was aligned along the longitudinal direction of the pressed sheet. The used dimensions for the tensile testing specimens were 32×6×3 $mm^3$. In order to examine the homogeneity of deformation, the Vickers hardness was measured along the central line of the transverse cross-section. The mean hardness values for each state were obtained from 10 measurements on each specimen.

In order to study the properties of a piece the HPT, initially a copper sheet prepared the thickness 1 mm and then Discs were cut in the diameter 10 mm. In all experiments, the speed of the lower jaw die is 1 rpm. Fig. 7, a copper disk in the jaw cavity pressure HPT shows.

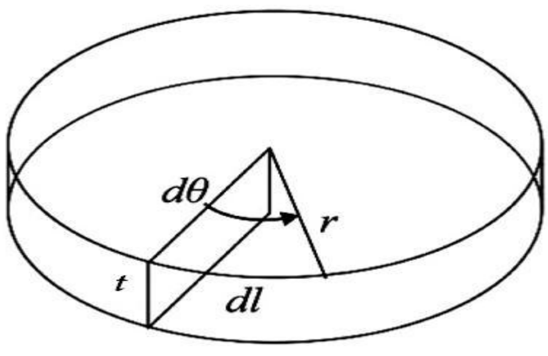


**Fig. 4. Parameters to calculate the angular strain in the HPT [1].**

**Fig. 5. Copper sample after pressing the 5 times.**

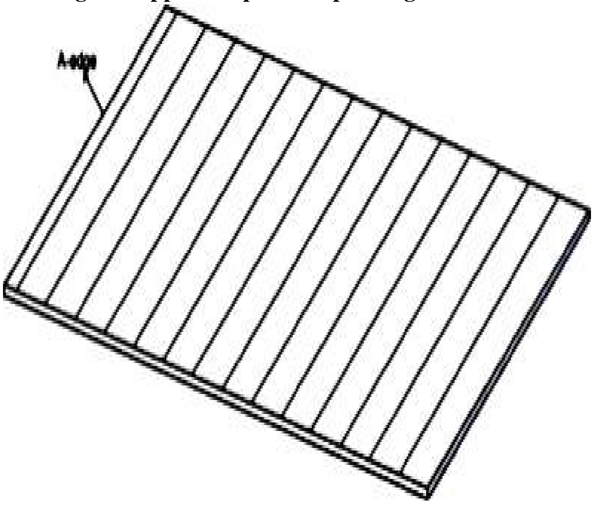

**Fig. 6. Hardness testing situations.**

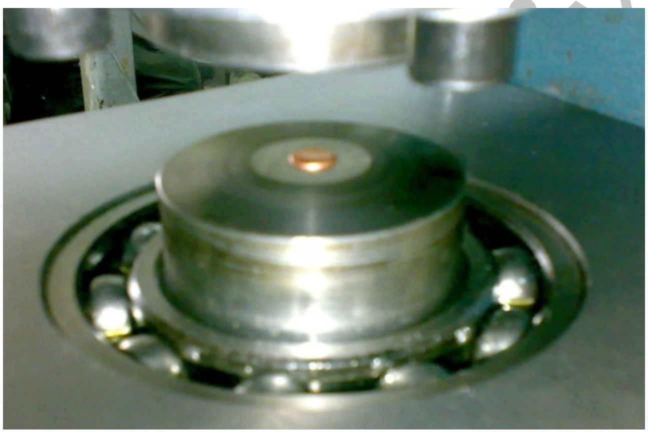

**Fig. 7. A Copper disk inside the cavity dies before process HPT.**

Imposed on the samples after the HPT process at several different pressures and revolution, the Vickers hardness testing was done on the samples. This test based on standard ASTM E10-04 with 95% confidence was performed. Each sample was tested five times at five different points; purpose of the study hardly changes in a radial direction, the five points in a radial direction from the center are located near the outer edge.

## 4. Results and discussion

### 4.1. Mechanical properties evolution under CGP

Fig. 8 shows the result of tensile tests for the constrained groove pressed copper sheets at room temperature. According to the Fig. 8, there is a rapid increase in the ultimate tensile strength (UTS) and yield strength (YS) of specimens after the first pass. However, this increasing trend decreases in the second pass. The sheets in the annealed condition had an ultimate tensile strength of 210 MPa. This value increased to 250 MPa after the first pass. Increasing in yield stress and UTS of specimens under the CGP can be explained by work hardening at initial stages. A large value of plastic deformation can occur in samples during the CGP process. These plastic deformations cause work hardening. At this stage grain refinement can be effective. Since the grain size in CGP samples is low, it concludes that yield and tensile stress rise according to Hall–Petch relationship. These two phenomena can help improve tensile properties [5].

Subsequent passes actually resulted in slightly lower tensile strengths. This strength dropping in tensile tests of specimens may be due to two reasons. The first cause is saturation in high levels of accumulated strain in bulk material. At this stage, grains contain a large number of dislocations and it is impossible to produce new dislocation in these grains. The second cause is micro cracks that initiate on the surface of specimens, especially in higher pass numbers, due to the friction and stress concentration on the corner of grooves [3,6,7,9].

The achieved strength values show a similar trend reported by researchers in previous works [3, 7-9]. Yield strength of specimens under CGP in the annealed condition were 63 MPa. After the first press this value increased to 210 MPa. Like ultimate tensile strength, there is a dropping in the yield strength of specimens after the second pass. From Fig. 8, it can be found that there is a decreasing trend in the elongation at fracture of samples in whole passes. Elongation of as-received sheets decreased from 0.51 to 0.14 after three passes. Decreased elongation in specimens can be justified by work hardening too.

### 4.2. Hardness under CGP

The main value of sheet hardness versus the number of passes is shown in Fig. 9. It can be observed that the hardness of samples under CGP is increased with increasing of the number of passes until the tertiary pass. In the tertiary pass the hardness of sample slightly decreases. Also, for studying of mechanical homogeneity, the hardness variation along the central line of the transverse cross-section for each pass has been brought in Fig. 10. It is clear that the imposed strain has become more uniform with increasing pass numbers. Since the hardness did not vary significantly in the tertiary pass. It implies that deformation imposed by the CGP technique with grooved and flat dies shown in Fig. 1 is quite uniform throughout the sample, ensuring good mechanical homogeneity.

### 4.3. Hardness under HPT

Fig. 11 shows the hardness and how to change it. In this figure, the diagram corresponds to hardness the disk at any point, when revolution number of fixed and variable pressure is plotted. As it is clear from this the diagram, the hardness a copper disk in the annealing is about 50 Vickers. The hardness initially applying the HPT process to increase quickly; especially, this increase is more severe near the edge. Whereas, after one revolution the hardness in pressure 0.64 GPA to more than 100 Vickers near the edge and the centerpiece has reached about 80.

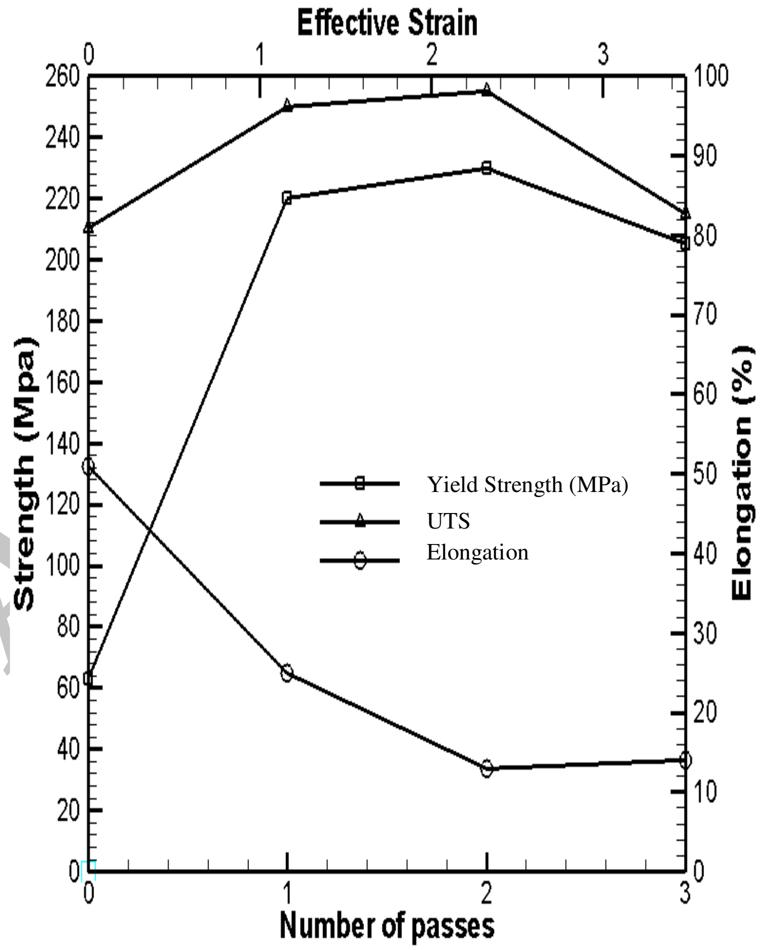


**Fig. 8. Tensile properties of Cu sheet with number of passes.**

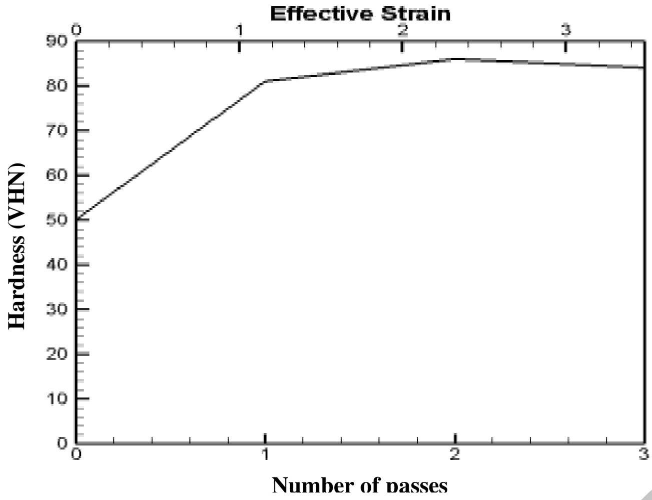


**Fig. 9. Vickers hardness vary with the number of passes.**

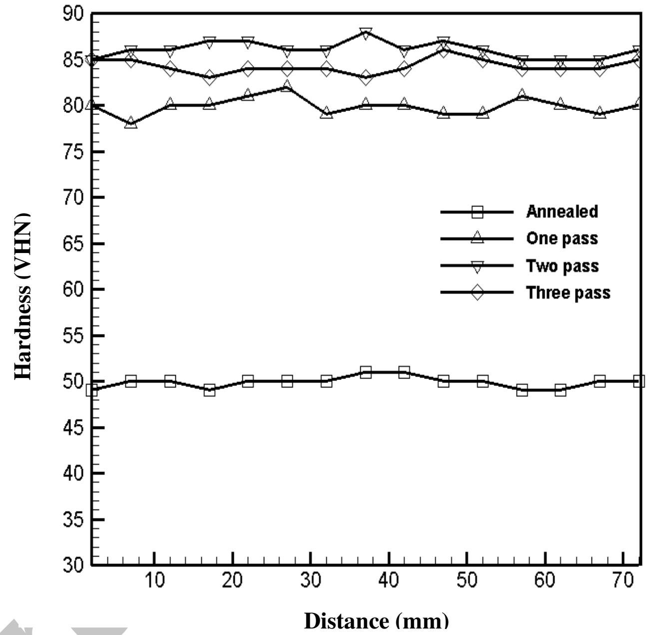


**Fig. 10. The Vickers hardness profile measured along the central line of the transverse cross-section.**

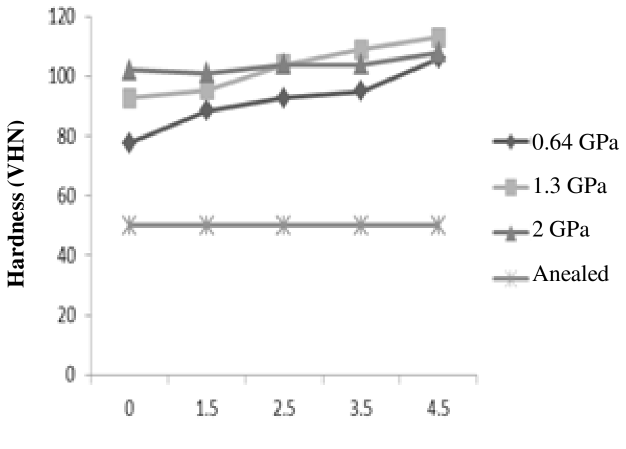


**Fig. 11. Hardness disk at any point under different pressures.**

Development process and increase the pressure, rate of increase in hardness near the outer edge of the piece is reduced. But the points near the center piece, the trend continues to increase the hardness, so that a continuous increase in hardness in the central points and reduces the rate of increase in hardness near the edge, disk uniformity can be improved gradually. Thus, with increasing revolution is expected, still hardness increased  and the behavior of pieces in the previous section again in the higher range of hardness is repeated. Fig. 12 has confirmed this. Trend of increase in hardness from the center toward the edges can be seen and the pressure effect is similar to the previous status. Pressure 2 GPa cause is maximum value hardness.

Fig. 13 shows diagrams similar to the fourth revolution. With a little care in the figure it can be seen that the trend of increasing of the hardness as the previous cases is not clear and prominent and we can say that by increasing the pressure too much, its effect is relatively reduced. The reason for this phenomenon can be sought in the loss of compressive force. In other words, with increasing pressure, due to the elastic deformation of the mold components, geometric tolerances and others cluttered and function of die will be a trouble. Thus, it may which the die Jaws have to deal together. Therefore it seems that the existing equipment decrease in performance at pressures more than 3 GPa and the pressure applied will not pass to pieces completely.

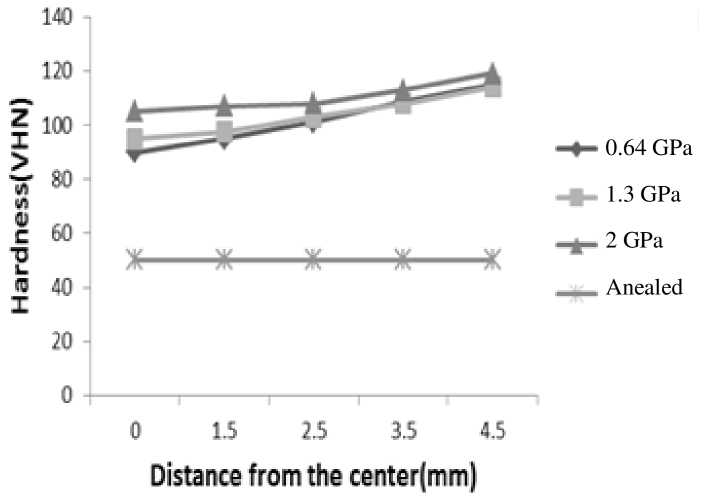


**Fig. 12. Hardness disk at any point under different pressures.**

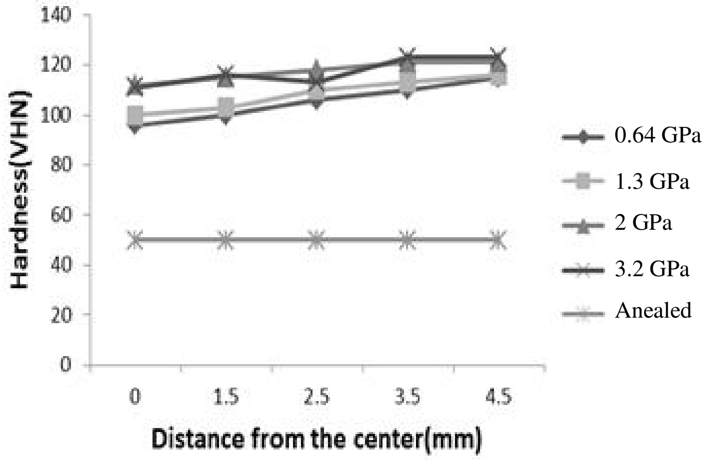


**Fig.13. Hardness disk at any point under different pressures.**

## 5. Conclusions

In the present study, constrained groove pressing (CGP) and high pressure torsion (HPT) processes as effective methods of severe plastic deformation (SPD). For the strain imposed on the samples of pure copper was applied successfully. On the total, effective strain of 3.48 was imposed to CGP samples during three passes.

The results showed that the tensile strength of specimens increased until the second pass; however, subsequent passes actually resulted in slightly lower tensile strengths indicating some degree of flow softening and existence of surface micro cracks. Hardness of specimens continuously increased with increasing of the pass numbers. Also, a loss of ductility was observed in all processed sheets.

In the HPT process hardness specimen was non-uniform and with increasing distance from the center it steadily increases. This phenomenon is due to HPT process of rotational nature. In fact, the amount of strain at any point of the pieces as it is applied directly related to its distance from the center. Points are close to the edge of pieces further distance from the center so the maximum plastic strain is applied to a region close to the environment. This shows the maximum amount of hardness in this area. In brief, according to obtained result, Constrained Groove Pressing Technique is a very suitable method for production of ultra fine grained sheets with uniform mechanical properties throughout the specimens but HPT method creates a non-uniform mechanical properties.

### Nomenclature

| | |
|---|---|
| $\varepsilon$ | Strain |
| $\Theta$ | Angle |
| t | Thickness |
| r | Radial |
| $\sigma_0$ | Pure shear stress |
| k | Constant yield |
| $\gamma$ | Shear strain |

### Subscripts

| | |
|---|---|
| Eff | Effective |
| Y | Yield |

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