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Effects of Constrained Groove Pressing (CGP) on the plane stress fracture toughness of pure copper

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Abstract. Among severe plastic deformation methods, groove pressing is one of the prominent techniques for producing ultra-fine grained sheet materials. This process consists of imposing repetitive severe plastic deformation on the plate or sheet metals through alternate pressing. In the current study, a 2 mm pure Cu sheet has been subjected to repetitive shear deformation up to two passes. Hardness and tensile yield and ultimate stress were obtained after groove pressing. Fracture toughness tests have been performed and compared for three conditions of sheet material namely as received (initial annealed state), after one and two passes of groove pressing. Results of experiments indicate that a decrease in the values of fracture toughness attains as the number of constrained groove pressing (CGP) passes increase.

Keywords: Constrained Groove Pressing (CGP); copper; fracture toughness

1. Introduction

Mechanical and physical properties of metallic materials in addition to their elements, somewhat depend on microstructure and grain size. Severe plastic deformation (SPD) is one of the best approaches to create metallic material with ultra-fine grain (UFG) (Iwahashi *et al*. 1998, Furukawa *et al*. 2001a, b). Materials produced by SPD are no porosity and have desirable mechanical properties such as strength and toughness (Rajinikanth *et al*. 2008). Some common methods in SPD include Equal Channel Angular Pressing (ECAP) (Krishnaiah *et al*. 2005), Accumulative Roll Bonding (ARB) (Krishnaiah *et al*. 2005, Lee *et al*. 2003), repetitive corrugation and straightening (RCS) (Krishnaiah *et al*. 2005), and Constraint Groove Pressing which is practical for sheet metals (Park *et al*. 2001, Shin *et al*. 2002, Krishnaiah *et al*. 2005, Khodabakhshi *et al*. 2010, Rafizadeh *et al*. 2009, Morattab *et al*. 2011, Zrnika *et al*. 2009).The basis of CGP process is that metals is undergone repetitive shear deformation under plastic strain condition by using periodic pressing with asymmetrically groove dies and flat dies (Krishnaiah *et al.* 2005). Up to now, a lot of studies have been carried out mainly on microstructures evolution, mechanical properties , and strengthening mechanism of UFG materials prepared by CGP (Khodabakhshi *et al*. 2010, Rafizadeh *et al*. 2009, Morattab *et al*. 2011, Zrnika *et al*. 2009). Many

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researchers have worked on obtaining the fracture properties in various materials such as Q345 steel; polymer concretes (Liao *et al.* 2012, Aliha *et al.* 2012). With regard to engineering applications, more attentions have been paid to the study of fracture and fatigue properties lately by Kunz *et al.* (2005), Agnew and Weertman (1998).

In recent years and in lots of research, fatigue properties of specimens produced by Equal Channel Angular Pressing (ECAP) have been investigated by Xua *et al*. (2008), Patlan *et al.* (2001), Zhang *et al.* (2005), Kulyasovaa *et al.* (2009). According to the authors' knowledge, there is not considerable study on fracture properties of materials that prepared by CGP.

In this research, plane stress fracture toughness of CGPed pure copper commercial sheets is investigated. In addition characteristics of deformed sheets are obtained, using tensile and hardness tests. In order to establish the fracture toughness Mode I, the specimens is subjected under CGP process, designed to Compact Tension test (CT). Plane stress fracture toughness is not inherent material property and has instable measure because its value depends on geometry. This article aims to compare fracture toughness values between different variable passes of CGPed pure copper commercial sheets.

2. Constrained Groove Pressing (CGP)

A schematic of the CGP is presented in Fig. 1. A plate-shaped work piece is located between a pair of asymmetrically grooved dies that are tightly constrained. As the dies press the work piece, the inclined regions of the work piece (single hatched regions in Fig. 1(b)) are subjected to shear deformation under the plane-strain deformation condition (ε_{eff}=0.58), while the flat regions (un-hatched regions in Fig. 1(b)) remain unchanged. A pair of flat dies imposes a second pressing on the grooved work piece (Fig. 1(c)) in which the deformed regions are subjected to the reverse shear deformation (ε_{eff} =1.16) while the un-deformed regions remain unchanged. The work piece is then rotated 180^{o} (Fig. 1(d)), allowing the un-deformed regions to be deformed by further pressings by the asymmetrically grooved dies. The successive pressings by grooved dies (Fig. 1(e)) and flat dies (Fig. 1(f)) result a nearly even distribution of plastic strain (ε_{eff}=1.16) throughout the work piece and one pass of CGP accomplished. By repeating the CGP process, a large amount of plastic strain can be accumulated in the work piece without changing its initial dimensions (Lee and Park 2002). The theoretical relationships for estimating shear strain and effective strain in this configuration after two CGPed cycles are displayed in Eqs. (1) and (2), respectively (Niranjan and Chakkingal 2010).

$$\gamma_{xy} = \frac{t}{t} = 1 \tag{1}$$

$$\varepsilon_{eff} = \sqrt{\frac{4(\gamma_{xy}^2/2)^2}{3}} = \frac{1}{\sqrt{3}} = 0.557 \tag{2}$$

The geometrical parameter, *t*, is shown in Fig. 1(a). After the first pressing pass the process can be continued through two approaches. In the first approach, named single-orientation pressing, the inclined regions of the plate after every pass remain parallel to the previous pass. In the other approach (cross-orientation pressing), the inclined regions of the plate after every pass are perpendicular to the previous pass. In other words after every pass the plate is rotated 90° around

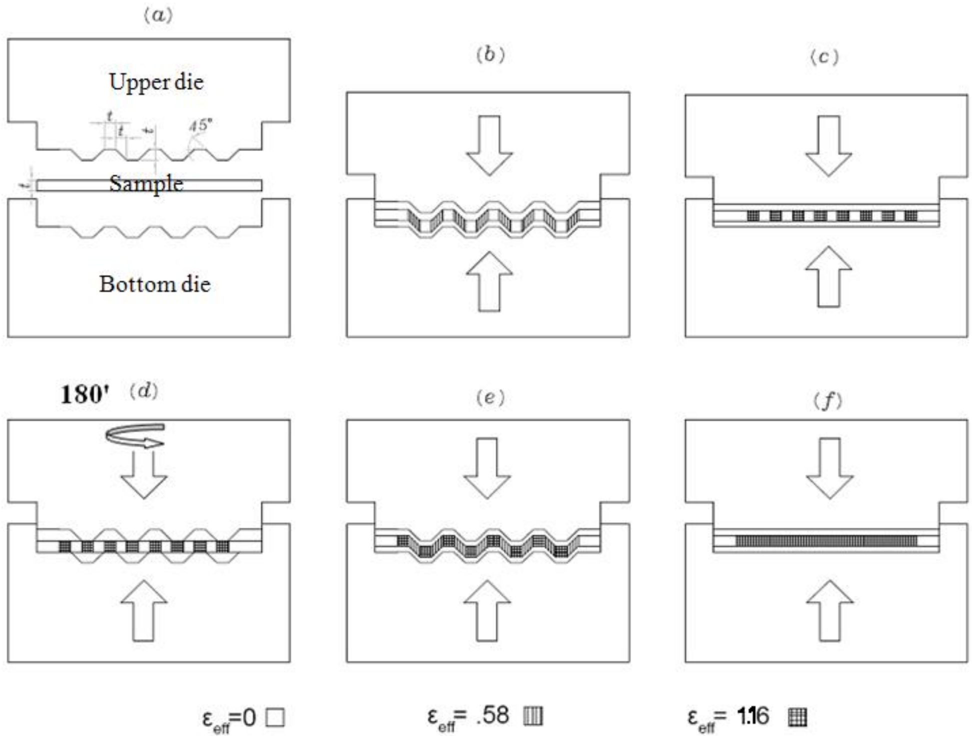

Fig. 1 A schematic illustration of the sequences of the constrained groove pressing (CGP)

Table 1 Chemical composition of used Cu

Cu	Zn	Fe	Ni	Co	Cd	Si	Mn	Al	Pb	Sn
99.11	0.557	0.08	<0.005	0.0530	0.014	<0.005	0.0064	<0.01	0.132	0.015

the vertical axis. The second approach has some advantages such as higher grain refinement rate and lower crack propensity due to more even distribution of bending and stretching locations where the materials are subjected to the most severe loading condition and thus prone to cracking (Peng *et al.* 2009). The present study is led by the latter approach.

3. Experimental procedures

In the present study pure copper commercial plates with dimensions of 88 mm×88 mm×2 mm were pressed up to two passes using cross-orientation pressing approach. The applied grooved dies in CGP prossess are shown in Fig. 2.

The chemical composition of the CGPed copper is shown in Table 1. Before pressing, the copper sheets were annealed at 923K for 2h. The pressing cycles were conducted up to a total of eight pressing. After that, it results in some micro cracks developed on surface where the material is subjected to the most severe loading condition. The whole pressing operation was carried out using a 50ton hydraulic pressing machine operating at a constant press speed of 0.1 mm/s at room temperature.

Fig. 2 Grooved die and copper sheet after the first groove pressing of CGP

3.1 Tensile and hardness tests

After completion of CGP process on cooper sheets, by applying wire-cut machine, tensile test specimens prepared from CGPed sheets by considering ASTM-E8M specimen preparation limitations,. Tensile testing was carried out on specimens with gage length 28.8 mm, width 5.4 mm and thickness 2 mm using a 50 kN tensile testing machine at a cross head speed of 0.15 mm/s. Two tests were conducted for each condition. Micro hardness measurements were made on the longitudinal sections along the length of the specimen. A 15 kg load applied for 15 s was utilized for these measurements, Vickers hardness test was performed according to ASTM E92-04. Besides, the microstructure of processed specimens was observed by an optical microscopy to investigate the effect of increasing pass on grain size distribution of CGPed sheets.

3.2 Fracture test

To achieve the main purpose of this process, the specimens were tested in three states of CGPed pure copper. Complying with ASTM E647 standard, CT specimens are prepared from the deformed copper sheets using wire-cut machines. Pre-cracks are made in the specimen through wire-cutting technique. This pre-crack creation approach was approved several years ago by Mourad *et al.* (2005). The specimen size was 23.75 mm×22.8 mm×2 mm thick which is shown in Fig. 3. In the specimen a narrow slit of approximately 2mm width and 12mm length was introduced by machining. It was terminated into a 60° v-notch. The tip of the v-notch was further extended up to 1 mm with (a_0/W) ratio equal to 0.45. This extension was done through wire-cut machining with the wire radius of 100 μm. Three different prepared specimens are shown in Fig. 3. It is to be noted that the CT type specimen is under purely Mode I loading condition. All of fracture tests are carried out in displacement control at a constant rate. The experimental set-up of CT specimens was shown in Fig. 4. Specimens were loaded quasi-statically at a moving head speed of 0.1 mm/min up to the maximum load and beyond on a SANTAM grip, until the specimens rupture. Three or four samples were tested for each pass type of specimens.

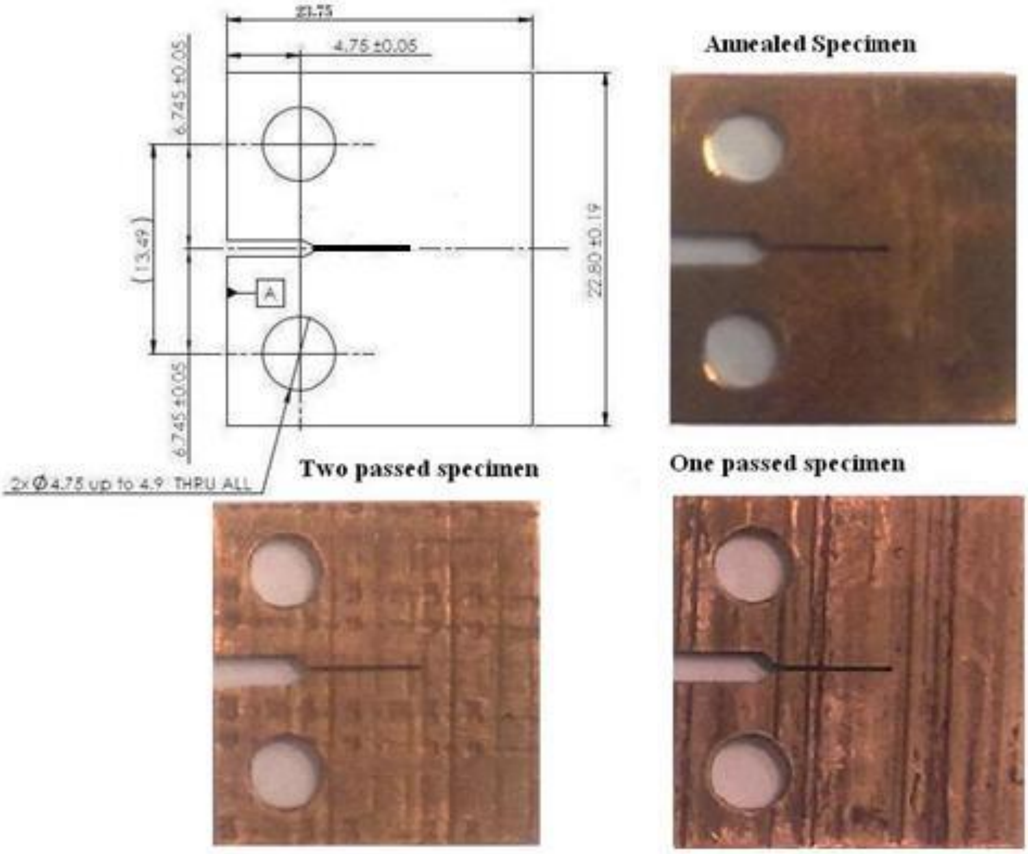

Fig. 3 Annealed, one, and two passed CT specimens of CGPed copper

According to ASTM E-561, the plane stress fracture toughness of the specimens, *Kc*, can be obtained. It is noted that, the value of K_C must be captured at the instability condition from the tangency between the *R*-curve and the applied *K*-curve of the specimen. In addition, using ASTM-E8M, for the CT specimens, the crack grows resistance, K_R, can be determined as follows

$$K_R = (\frac{P}{B\sqrt{W}}) \times f(\frac{a}{W}) \tag{3}$$

where:

$$f\left(\frac{a}{W}\right) = \left[\frac{2+\frac{a}{W}}{\left(1-\frac{a}{W}\right)^{\frac{3}{2}}}\right]\left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.6\left(\frac{a}{W}\right)^4\right]$$

which it is valid for any $\frac{a}{W} \geq 0.35$. The size requirement is to ensure the validity of the linear elastic fracture mechanics calculations. The parameter *P* in Eq. (3) is the load at the 0.2% propagation of crack which is obtained in the load-displacement curve of CT specimens obtained from experiment. *W*, *B* and *a* are the span, width, thickness and the total crack length of the CT

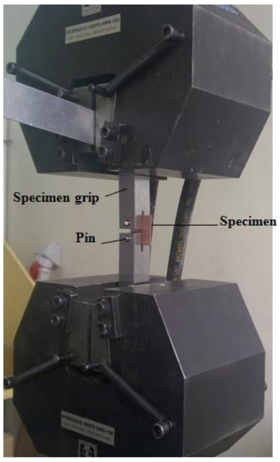

Fig. 4 Experimental set-up

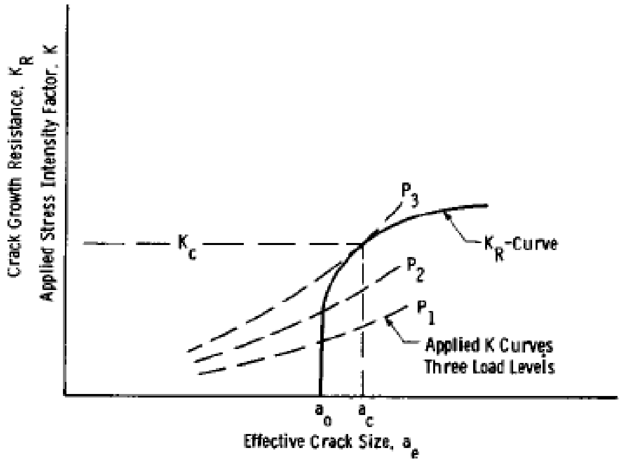

Fig. 5 Schematic *R*-curve; K_C occurs at the point of tangency between the applied *K*-curves at different load level and *R*-curve

sample, respectively. Also, *f* in Eq. (3) is a dimension factor that depends on the ratio of (*a/W*), which is defined in ASTM-E561.

As the crack begins to grow, K increases with crack growth until a steady state value of *K* that the *R*-curve becomes flat in this condition. In this state, it is possible to define critical stress intensity factor, K_C, which occurs at the point of tangency between the applied *K*-curves at different load level and *R*-curve. A Schematic *R*-curve is presented in Fig. 5. It is shown that the K_C occurs at the point of tangency between the applied load and *R*-curve. This instability point is not material property, and it might be changed with geometry and porosity and flaw on the surface of material. In this study we obtained *R*-curve concurrent with *Kc* for the prepared specimens.

4. Result and discussion

In following section, the mechanical materials properties and plane stress fracture toughness of prepared specimens from annealed and different pass of CGP process will be obtained.

4.1 Mechanical materials properties

After pressing the copper sheet-form specimens up to failure, tensile tests and hardness measurements have been carried out to obtain mechanical properties of sheets from each pass. It is worth noting that the Cu sheet in die where angle is equal to 45° is pressed up to two passes. Fig. 6 illustrates the magnitudes of yield strength, ultimate tensile strength and elongation to failure versus the pass numbers in this work. For these specimens, it can be observed that increasing number of passes results in high value of yield and ultimate tensile strengths up to 2 passes. The same tendencies had been reported in previous studies by Krishnaiah *et al.* (2005). Also, the fracture elongation value is decreased by increasing pass number. The value of YS and UTS at final pass situation are 195 MPa and 245 MPa, respectively. The fracture elongation decreases from 43% to 18% after the first pass which reaches to its minimum value after two passes.

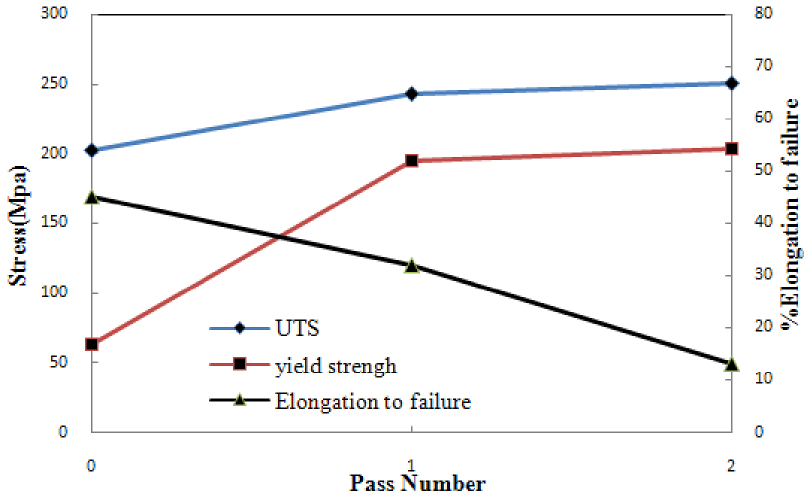

Fig. 6 Tensile properties of different CGPed pass of copper sheets

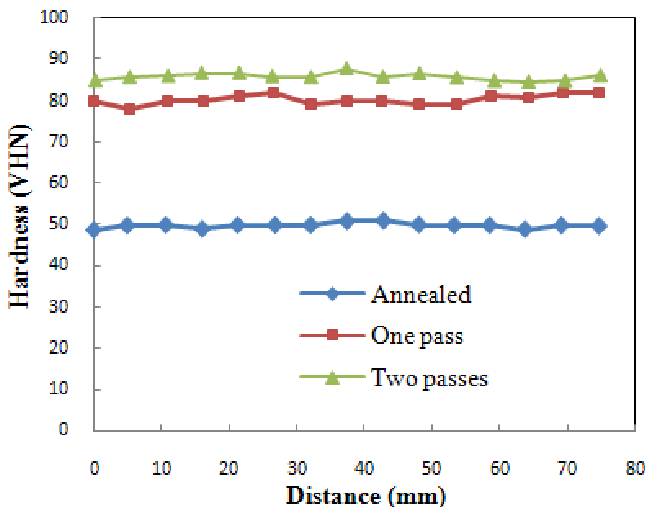

Fig. 7 The distribution of hardness measurements for specimens at each pass number

To investigate hardness distribution in the longitudinal direction of the sheet, hardness tests accomplish in the centerline of sheet by the increment of about 8 mm (the total number of 11 measurements). Fig. 7 represents the distribution of hardness measurements for specimens at each pass number. It can be shown that, after one pass, the hardness of specimens increases about 160%. But in the second pass, the increasing value is only 10% comparing with one pass CGP. By increasing the pass of CGP, increasing of hardness will be saturated.

To validate the reduction of grain size, micro structural changes during process are examined by optical microscope (OM) observation. The microstructure of copper sheets after CGP process was studied by Krishnaiah *et al.* (2005). Fig. 8 shows the microstructures of the groove pressed copper at room temperature in each pass respectively. The grain size of as-received, one passed up to four passed processed specimens were measured using optical microscope (OM). The sample

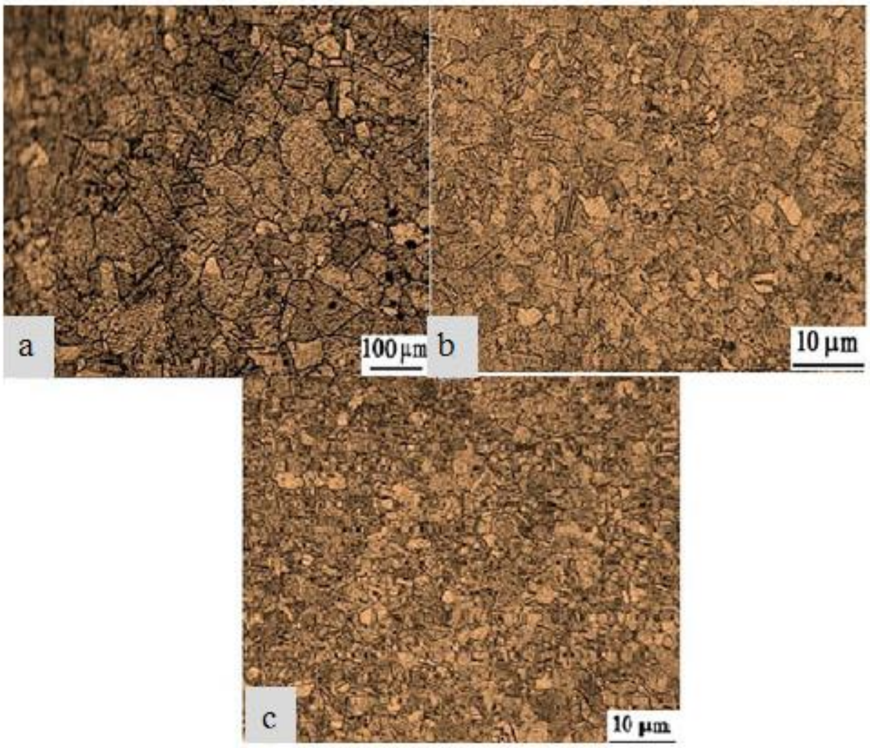

Fig. 8 Optical microscope (OM) microstructure of the commercially pure copper subjected to groove pressing specimens (a) as-received Cu specimen (b) OM micrograph after one pass (c) OM micrograph after three passes

were ground on papers, polished and then etched in a solution of 20 mg.L^{-1}HNO_3. The average grains size of as-received specimen is 60 μm as shown in Fig. 8(a). The refined grains size after four pressing cycle was 950 nm.

4.2 Plane stress fracture toughness

Critical stress intensity factors were calculated for all of the specimens using Eq. (2). In Fig. 9, CT specimens after loading were shown. It was observed that crack in Mode I was initiated and grown in straight line. In each case, the crack ignition and propagation lengths are different. In annealed specimen, the value of crack initiation length was 10.65 mm. Table 2 illustrates the maximum load and crack initiation values for each specimen type.

To measure the length of crack, there are two options, visually or an equivalent method according to ASTM standard E647. For visual measurements, the test area of the specimen should be polished and indirect lighting aid should be used in the resolution of the crack-tip. It is suggested that prior to testing, reference marks be applied on the test specimen at pre-determined locations along the direction of crack growth.

In equivalent method, an electrical potential difference (EPD) method was applied. In this work, visual method was used as well as taking advantage of a camera with optical zoom value around 60x. Fig. 10 shows the typical load–displacement curves of different type of CT test

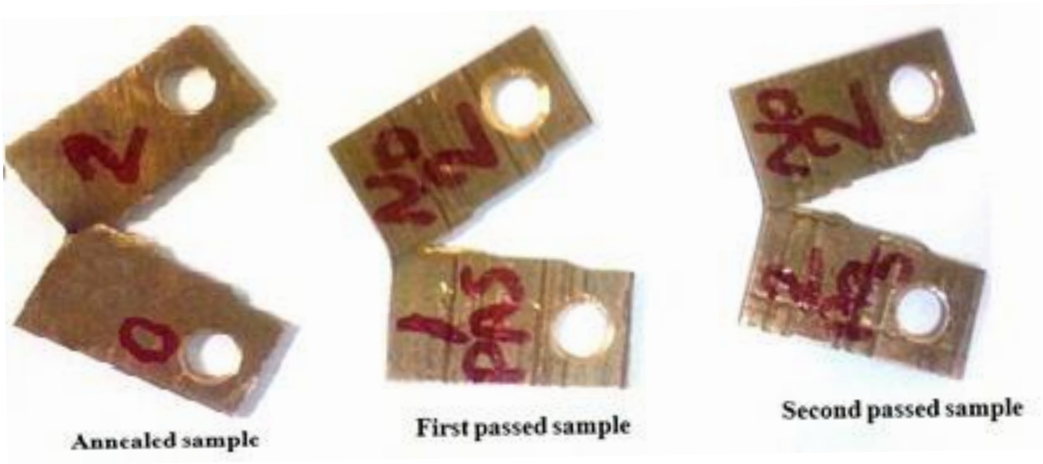

Fig. 9 CT specimens after fracture tests

Table 2 maximum load and crack initiation values for each specimen

Procedure	P_{max} (kN)	Crack initiation length (mm)
Annealed Specimen	0.32	10.65
First passed Specimen	0.54	9.65
Second passed Specimen	0.71	9.15

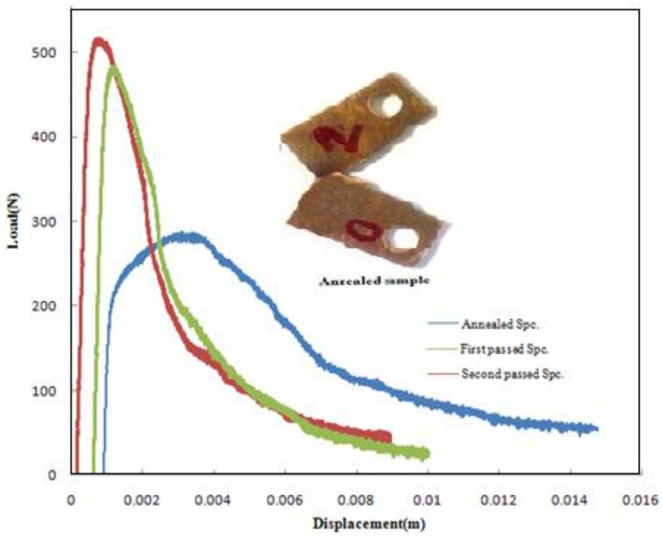

Fig. 10 Typical load-displacement curves in the CT tests of the annealed, first and second passed Cu specimens

specimens. In this figure, the cross-head displacement of specimen was used instead of the notch-opening displacement.

Clearly, the second passed sample bears the largest load for propagating the pre-existing cracks comparing with the annealed and first passed Cu samples. The provisional fracture toughness K_c of three samples was obtained according to Eq. (2) and standard E-561. *R* curve of annealed, one, and two pass of CGP process on copper sheet were shown in Figs. 11-13, respectively. Red color curve in each figure is *R*-curve of annealed, first and second passed samples. Blue dash-line curves present *K*-curve with different driving forces.

The value of K_C at each condition is obtained from the tangency between the *R*-curve (red curve) and the applied *K*-curve (blue-dash line curve) of the specimen. Table 3 indicates measured values of K_C. It can be observed that after two passes the value of plane stress fracture toughness increases. In annealed sample, K_C was measured as 13.5 MPa.m$^{1/2}$, and in first and second passed samples, K_C was obtained as 18.9 and 22.5 MPa.m$^{1/2}$ respectively.

It is noted that the applied *K*-curves in each case are determined by using both constant load and increasing amounts of crack length according to theoretical equations. An *R*-curve is a

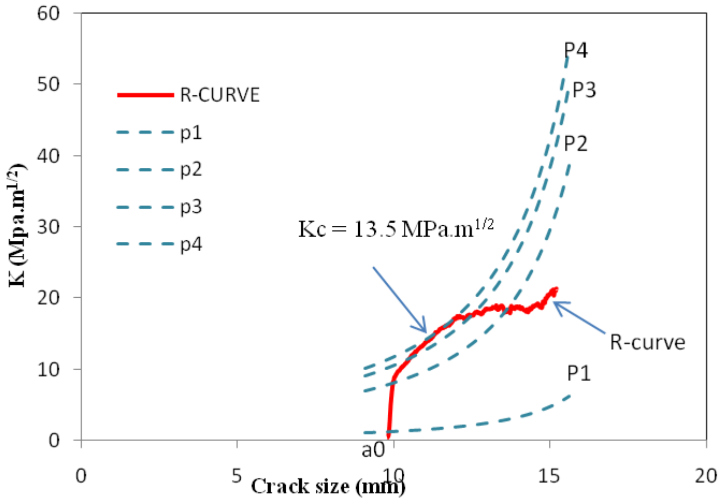

Fig. 11 *R* curve for annealed specimen

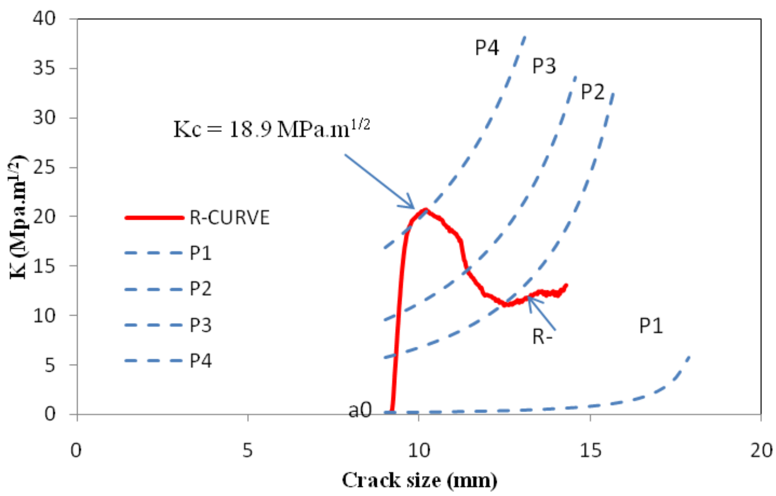

Fig. 12 *R* curve for first passed specimen

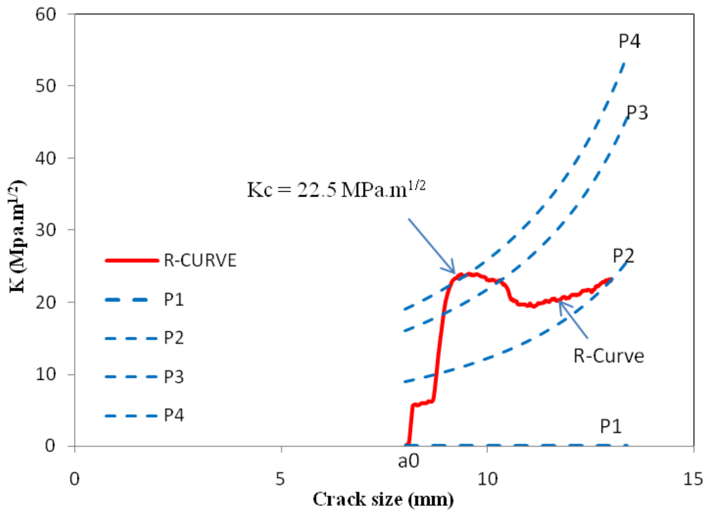

Fig. 13 R curve for second passed specimen

Table 3 The value of K_C at each specimen type

Procedure	K_C (MPA.m$^{1/2}$)
Annealed Specimen	13.5
First passed Specimen	18.9
Second passed Specimen	22.5

continuous record of K_R plotted against crack extension in the material as a crack is driven with a continuously increased stress intensity factor, K. For drawing the R-curve of each case, the K_R values were calculated from experiments from crack initiation up to unstable crack propagation using P value of each crack length which are recorded during the test.

It can be shown that applying constrained groove pressing on sheet metals up to higher passes, makes it possible to fabricate plate-shaped ultra-fined grained metallic materials without changing their initial sizes. Therefore the size of grains will decrease and the number of grains and boundary grains will increase. Total fracture energy is equal to product of energy per unit area and crack length (Anderson 1994)

$$E = \gamma \times L \tag{4}$$

Since CGP process has been carried out up to two passes on copper sheet, fracture surfaces develop, consequently according to Eq. (4), total fracture energy increases by increase of number of passes in each specimen. Also Qin *et al.* (2009) achieved the same results in the increase of fracture toughness in effect of ultrafine on copper at their experimental observations.

5. Conclusions

In this research, groove pressing was used for producing ultra-fine grained sheet materials. This process consists of imposing repetitive severe plastic deformation on the plate or sheet metals through alternate pressing. A 2 mm pure Cu sheet has been subjected to repetitive shear deformation up to two passes. Applying constrained groove pressing on sheet metals up to higher passes makes it possible to fabricate plate-shaped ultra-fined grained metallic materials without changing their initial sizes. Therefore the size of grains decreased and the number of grains and boundary grains increased. After four pressing cycle, the grains size was 950 nm. Appling one and two pass CGP, the hardness of specimen increased about 60% and 70% respectively. Also, by increasing the number of pass, the fracture elongation value was decreased from 43% to 12%. After two pass of CGP, the increasing of yield stress and ultimate stress were about 225% and 25% respectively. Plane stress fracture toughness of CGPed sheets was investigated using compact tension (CT) specimens. It is observed that after two passes, the value of fracture toughness considerably increased. K_C of annealed samples was measured, and in the first and second passed specimens, K_C increased 40% and 67% respectively.

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