Severe plastic deformation of Al-1%Cu Alloy processed by a Simple Cyclic Extrusion Compression technique

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Abstract: Severe plastic deformation is an effective method for improving the mechanical properties of metallic alloys through promoting the grain structure. In the present work, simple cyclic extrusion compression technique (SCEC) has been developed for producing a fine structure of cast Al-1 wt. % Cu alloy and consequently enhancing the mechanical properties of the studied alloy. It was found that the grain structure was significantly reduced from 1500 µm to 100 µm after two passes of cyclic extrusion. The ultimate tensile strength and elongation to failure of the as-cast alloy were 110 MPa and 12 %, respectively. However, the corresponding mechanical properties of the two pass CEC deformed alloy are 275 MPa and 35%, respectively. These findings ensure that a significant improvement in the grain structure has been achieved. Also, cyclic extrusion deformation increased the surface hardness of the alloy by 49 % after two passes. FE-simulation model was adopted to simulate the deformation behavior of the material during the cyclic extrusion process using DEFORMTM-3D Ver11.0. The FE-results revealed that SCEC technique was able to impose severe plastic strains with the number of passes. The model was able to predict the damage, punch load, back pressure, and deformation behavior.

Keywords: Severe plastic deformation, Simple Cyclic extrusion compression, Al-1%Cu Alloy, Finite element analysis.

1 Introduction

In recent years, a global trend in material researches for processing of metals through the application of severe plastic deformation (SPD) is conducted. SPD could induce ultrafine-grained structures of order 1 um or nanoscale grains without changing the shape through the application of considerably high pressures at relatively low operating temperatures, thus obtaining superior mechanical and physical properties which widely their commercial use[1]. It is well known that SPD can produce ultrafine grain structures that cannot be obtained by conventional thermo-mechanical treatment (TMT) techniques[2]. Furthermore, it can be performed in the mass production of UFG metallic materials [3]. Different techniques have been employed to prompt SPD of metals, for instance, equal channel angular pressing (ECAP) [4-6], accumulative roll-bonding (ARB) [7-9], high pressure torsion (HPT) [3-5], repetitive corrugation and straightening (RCS)[6, 7], cyclic closed-die forging (CCDF) [8], super short multi-pass rolling (SSMR)[9] and cyclic extrusion compression (CEC) [10-12]. In the last few years, cyclic extrusion compression (CEC) has attracted more attention as a powerful technique for severe deformation of materials. The advantage of CEC is the ability to refine the grain structure of hard-deformation metals by enforcing the material to deform under three-dimensional compression stress [13]. Additionally, it can be applied to metals and alloys with unlimited continuous deformation without promoting microstructural defects [13-15]. Recently, CEC was successfully applied to few number of materials to produce ultra-fine grain structures such as AZ31 alloy[16], Mg–Zn–Y–Nd alloy [17] and AM60B magnesium alloy[18]. Qiong et al. [17] studied the microstructural evolution and the mechanical properties of Mg–Zn–Y–Nd alloy prepared by CEC. They found that the grain structure
was strongly refined to 1 μm after CEC processing through dynamic recrystallization mechanism.

Similarly, Wang et al. [18] studied the microstructural evolution and the related mechanical properties of AM60B magnesium alloys after CEC deformation. They reported that the yield and tensile strengths and elongation to failure of CEC formed alloy are 196 MPa, 297 MPa and, 16 pct, respectively.

However, the corresponding properties of the cast alloy are 64 MPa, 201 MPa and, 11 pct, respectively. Al alloys bearing Cu have a wide applications as a structural engineering material in aerospace, automobile, and airplane applications [19]. It is well known that the cast Al alloys, which originally have low yield and tensile strengths, are unsuitable for structural applications, unless the mechanical properties are increased by aging treatment. However, the increase in the strength of Al alloys due to the heat treatments is not enough to satisfy the manufacturer’s demands. Therefore there is a growing interest to develop high-strength Al alloys for automotive applications demanding a good combination of high strength and ductility. Evidently, the CEC deformation of cast Al-Cu alloys has not yet been completely understood. Furthermore, most of the previous work published on Al-Cu alloys were carried out using a wrought structure.

In this study, a modified CEC technique has been employed to enhance the mechanical properties of as-cast Al-1 wt.% Cu alloy through refining the grain structure. Numerical simulations were implemented by using DEFORMTM-3D to analyze and calculate the equivalent plastic strain distributions in the material during CEC deformation and also predict the accumulated damage, punch load, back pressure, and deformation behavior in the workpiece.

2 Principle of extrusion compression

In the current work, the purpose of the simple design of the extrusion die channel is to guarantee an easy material flow in the die channel. Fig. 1 shows a structural drawing of the simplified extrusion system that has been adopted in this research. The channel of the extrusion die is shown in Fig. 1(b). It is divided into three zones (Zone I, Zone II and Zone III) with unequal lengths. The diameters of zone I and zone II are selected to be 10 and 6 mm, respectively, to achieve a significant high strain of 2 per cycle according to equation (1):

The accumulated true strain \( \varepsilon_a \) (due to successive extrusion and compression), was approximately given by [20]:

\[
\varepsilon_a = 4n \ln\left(\frac{D}{d}\right)
\]  

(1)

Where \( D \) is the die channel diameter, \( d \) is the small channel diameter (die throat), and \( n \) is the number of CEC passes. Hence, the amount of deformation can be controlled by continuous applying of the tension and compression forces.

According to Von Mises, the effective strain, \( \bar{\varepsilon} \) is defined as:

\[
\bar{\varepsilon} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2}
\]  

(2)

Where \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \) are the principal strains.

In the SCEC process, the work-piece is squeezed through a die channel which consists of three zones as shown in the schematic diagram of Fig. 2. In the entry channel (zone I), the work-piece experiences no deformation and is forced to move toward the deformation zone which lies between zone (I) and zone (II). In this zone, the work-piece undergoes high strain deformation, since the cross-section decreases from 10 at the entrance to 6 mm at the exit. This means, in one
pass the rod undergoes a true strain $\varepsilon_a = 2$ and effective strain $\bar{\varepsilon} \approx 4.3$ whereas at the die throat, zone (II), the rod does not experience any reduction in the area.

In Zone III, the work-piece expands without deformation as in Zone I and die throat (Zone II) since the cross-sectional area of the work-piece does not change after extrusion deformation. Also, the workpiece material leaving the die throat after extrusion zone is not subjected to frictional force or geometrical constraint. Therefore it passes freely without additional deformation until it touches the upper part of the stationary plunger. At that time the back pressure starts to increase and resist the material from further axial deformation, but the workpiece expands in the radial direction filling the cavity of the zone (III), Fig. 2(b).

In Fig. 2(c), the deformation direction is reversed by turning the die 180°. Consequently, Zone III will act as Zone I in the second pass of extrusion deformation. This procedure allows repetition of the process for several times and enables high strain which is the major key factor in SPD mechanism.

The corners between the different zones of the die are machined to have 2mm fillet radius to improve metal flow in the deformation zone and prevent sticking of the work-piece at the intersection points of the die zones.

**Figure 1.** Schematic illustration of cyclic extrusion compression CEC), depicting the die consisting of three zones: (a) designing die and (b) experimental die showing gradual changes in the cross-sectional shape throughout the die.
3 Experimental procedure

3.1 Materials

The aluminum-copper alloys, Al-Cu, used in the present work were supplied as-cast material by EGYPTIAN COPPERWORKS company (Helwan-Egypt) in the form of rods with 300 mm length and 20 mm in diameter. The typical chemical composition of the studied material is shown in Table 1. Subsequently, bars of Ø10 ×60 mm were machined for cyclic extrusion compression testing with their axes parallel to the longitudinal direction of the ingots. These specimens were solution treated in a muffle furnace at 550 °C for 60 min to dissolve the second phases followed by quenching in cold water.

Table 1. A typical Chemical composition of the studied Al-Cu alloy (in wt.%).

| Element | Al  | Cu  | Zn  | Si  | Fe  | Mn  | Ti  | Ni  | Pb  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| wt. %   | Balance | 1.02 | 0.008 | 0.12 | 0.17 | 0.003 | 0.009 | 0.001 | 0.001 |

3.2 Materials Extrusion Processing

CEC experiments were performed at room temperature using a hydraulic press with ram Speed of 10 mm.s⁻¹. The surface friction expected between the work-piece and the die walls was reduced by using a lubricant of molybdenum disulfide (MoS₂). The work-piece has undergone two passes of CEC deformation by reversing the die 180°, see Fig. 2. The deformed microstructures through the CEC deformation straining of the Al-Cu alloy have been studied by using a scanning laser microscope (KEYENCE/VK-X200). Krolls Reagent was used as an etching solution (92 ml Distilled water, 6 ml Nitric acid and 2 ml Hydrofluoric).

The uniformity of the strain distribution and the homogeneity of deformation in the specimens after 1pass-CEC and 2pass-CEC were investigated by employing Vickers microhardness measurements and tensile tests. The microhardness measurements were carried out on the normal plane of the sample to the extrusion direction with applying a load of 980 mN. The mechanical properties, yield and tensile strengths and elongation, were measured by uniaxial tensile tests at a constant crosshead speed of 1 mm/min using a Shimadzu Autograph AG-50kNX precision universal tensile testing machine. The gauge length was short 6 mm. Three samples were tensile tested for each pass-CEC.

3.3 Finite element simulation model
The finite element (FE) simulations were conducted to study the deformation mechanism and the material flow during the CEC process using the commercial finite element software, DEFORM™3D Ver. 11. The 3-D model of CEC used in the simulations was created by 3D CAD software. Concerning to the material employed in the FE- simulations, the Al-1%Cu alloy, whose flow stress obtained from the tensile test is depicted in Fig.3 has been selected. The Die, the punch model, and the plunger have been defined as rigid bodies because of their insignificant elastic deformation during the extrusion process. The specimen has been defined as a plastic material and simulated as uniform material. Strain hardening properties of workpiece material were determined experimentally. The yield stress of metal under uniaxial conditions as a function of strain (\(\varepsilon\)), strain rate (\(\dot{\varepsilon}\)), and temperature (T) can be considered as flow stress. The metal begins deforming plastically when the applied stress reaches the value of yield stress or flow stress.

\[
\sigma = \sigma (\varepsilon, \dot{\varepsilon}, T)
\]

(4)

Automatic meshing was used to accommodate large strains. The frictional contact of the die and the workpiece was set as the constant friction of 0.08 and the friction type considered as shear. The punching speed was set as 10 mm/s to guarantee quasi-static state of deformation and the effect of strain rate is neglected. The type of simulation was Lagrangian Incremental. The tetrahedral element type was selected for the mesh processing of workpiece. In general, convergence of damage models doesn’t depend only on mesh quality. However, the mesh sensitivity test has been performed in order to visualize the convergence of CEC process simulation. In this regard, five simulations with total element numbers of 10000, 15000, 20000, 25000 and 30000 were set out, and the variation of the strain energy per unit volume during the simulation was controlled as summarized in Fig.(4). Regarding the convergence when refining the mesh, it is shown that the minimum strain energy occurred at 15000-element mesh then increased with increasing the mesh density. Accordingly, the 15000-element mesh was more suitable in simulation since it gave a better convergence and less simulation time with low energy. To estimate the damage in the rod during the process, a model type Cockcroft–Latham [21] has been considered. The Cockcroft and Latham damage criterion eq. (5) is defined as the integration of the ratio of maximum tensile stress \(\sigma_T\) to effective stress \(\sigma\) occurs through the applied equivalent strain \(\varepsilon\) in a metal-working process.

\[
D = \int_0^{\varepsilon_f} \frac{\sigma_T}{\sigma} \, d\varepsilon
\]

(5)

where \(\varepsilon_f\) is the total equivalent strain at the end of forming process which corresponding to \(D_{max}\) and is defined as ductile fracture criteria (DFC) or that is the critical damage value of the workpiece to fracture simply identifies the dependence of the critical value at fracture based on the level of the largest principal stress[22].
4 Results and discussions

4.1 The microstructure evolution

The microstructural observations of the studied Al-1Cu alloy revealed a matrix of the α-fcc structure with a significant large grain size of 1500μm after solution treatment A dendritic solidification pattern is seen in the microstructure, as shown in Fig. 5(a). Two examples of the resulted grain structure after one and two passes of CEC deformation, are shown in Fig. 5(b) and Fig. 5(c), respectively. It is apparent from the observations in the present microstructures that the grain structure has been enhanced with CEC deformation due to reducing the grain size. Many small new grains are found in the CEC deformed structure after two passes, see Fig. 5(c). These new grains are attributed to the dynamic recrystallization (DRX) mechanism that occurs during the extrusion. It is well known that the DRX plays an important role in refining the grain structure during SPD[23, 24]. Moreover, it is easily observed that the grains of the CEC structure are finer than those of the as-cast alloy. Since the average grain size decreases from about 1500 μm to 100 μm when the cast Al-1Cu alloy were cyclic extruded two passes with a cumulative deformation strain 4.

4.2 Mechanical properties

Fig. 6 showed the typical tensile engineering stress-strain curves of as-cast and extruded Al-1Cu alloy at room temperature. The mechanical properties, yield strength (YS), ultimate tensile strength (UTS) and elongation, are listed in Table 2. It is apparent from the tensile curves that the effect of the CEC deformation is very pronounced. Since the mechanical properties are markedly higher after two passes-CEC deformation. It is seen that the quasi-static mechanical properties of the as-cast Al-1Cu alloy are characterized by low yield and tensile strengths. The YS and UTS of as-cast specimens arrive only at 60 MPa and 110 MPa respectively. The elongation is small approximately 12 % due to the cast defects and dendritic structure. The strength and elongation of the extruded alloy are dramatically increased, as shown in Table 2. For example, the UTS and elongation of extruded Al-1Cu specimen are 270 MPa and 35%, respectively. These values of mechanical properties are considerably higher than that of the as-cast alloy, i.e., the UTS and the elongation are improved by 145% and 191%, respectively after two passes of CEC deformations.

This finding is in agreement with the work of Yeh et al. [25] who observed that in the extruded cast Al-20 wt.% Si alloy, the defects of the cast structure such as pores and microvoids undergo healing at their interfaces due to the high compression deformation. Consequently, the ductility
of the extruded cast Al-20 wt.% Si was improved significantly to a higher value than that in the as-cast alloy.

![Figure 5. Optical microstructures of the studied Al-1Cu alloy: (a) as-cast structure; (b) extruded alloy with one pass; and (c) extruded alloy with two passes.](image)

It is apparent from the obtained results that the CEC process is effective for enhancing the cast structure of Al-1Cu alloy, which leads to a significant increase in the mechanical properties. Table II. Mechanical properties of the as-cast and extruded Al-1Cu alloy with different passes of extrusion deformation at room temperature. The hardness was also measured across the cross-section of the extruded specimens comparing with the as-cast specimen. We found that the hardness significantly varies through the CEC deformation.

![Figure 6. Engineering stress–strain curves of the Al-1%Cu alloy at room temperature: (a) as-cast (green line), (b) 1 pass-extruded alloy (black line), and (c) 2 pass-extruded alloy (red line).](image)

**Table 2.** Mechanical properties of the as-cast and extruded Al–Cu alloy with various passes.
| Property          | As-cast | 1 pass-extruded alloy | 2 pass-extruded alloy |
|-------------------|---------|-----------------------|-----------------------|
| YS, MPa           | 60      | 90                    | 149                   |
| UTS, MPa          | 110     | 210                   | 270                   |
| Elongation, %     | 12      | 27                    | 35                    |

Fig. 7 shows the hardness variation with the extruded Al-1Cu alloy with the number of CEC passes. It is clear that the hardness is noticeably affected by the number of deformation passes. Since the hardness increased from ~50.6 Hv to 66.2 Hv after 1 pass-CEC. As the CEC deformation proceeds to the 2nd pass, the hardness increases to 75.5 HV. It is well established that with SPD as in the present work, slip bands and high dislocation densities are induced in the structure. This can lead to hardening the structure. Also, the increase of microhardness values may be ascribed to the formation of subgrain structure and small new grains due to operating dynamic recrystallization mechanism during SPD [26, 27]. It is clear that the more extrusion passes, the better the mechanical properties.

![Figure 7](image)

**Figure 7.** Dependence of hardness of Al-1Cu alloy on the extrusion compression passes.

### 4.4 Fractography

The fracture surfaces of the extruded Al-1Cu specimens after tensile testing are shown in Fig. 8. Fig.8 (a) shows the fracture surface features of the as-cast Al-Cu alloy. It can be seen that the dendrite structure and microvoids surrounded by clear indications of cleavage planes are present. It is clear that the fracture mechanism of the as-cast specimen is mainly attributed to brittle fracture. Hence, the lacking in significant ductility of the cast alloy is attributed to the defects in the cast structure.

The fracture surface of the extruded Al-1Cu alloy after 1 pass-CEC is shown in Fig. 8(b). It can be observed that the dendrite structure disappears from the fracture surface. On the other side, the dimples in the extruded alloy display on the fracture surface. With increasing the extrusion deformation to 2-pass, the density and size of dimples in the extruded alloy are increased on the fracture surface, see Fig.8(c). This is clear evidence
of enhancing the mechanical properties, particularly good ductility, with CEC. These observations are fully consistent with the tensile test results in the present work. In agreement with that work, Fu et al.,[28] observed that the density and size of dimples in the fracture morphology of the extruded Mg-8Li-1Al alloy are increased on the fracture surface. Thus, the extrusion process is an effective technique to enhance the mechanical behavior of test specimens.

![Figure 8. SEM micrographs of the tensile fracture surfaces of Al-1Cu: (a) as-cast alloy; (b) extruded 1-pass CEC and (c) extruded 2-pass CEC.](image)

### 4.5 Simulation results

#### 4.5.1 Total Equivalent Plastic Strain

Figure 9 shows the equivalent plastic strain distribution of the Al-1%Cu alloy after one-pass of CEC. It is seen that at initial deformation steps, e. g. Step 50, the metal rod is extruded into a small rod with a cross-section area similar to the die throat (small extrusion channel) and continue to flow sideways free without any obstacles till it reaches to the top surface of the plunger. When the small rod touches the plunger surface, it is exposed to back pressure and be under compressive load. As the flow of the metal increases due to extrusion, the compressive load (plunger back pressure) will increase and cause buckling of the rod (see step100). The rod buckling opposes the metal to flow toward the bottom of the rod near the plunger surface. So, the cross-section area of the rod beneath the extrusion channel gradually starts to increase and fill the cross-section area of the cavity (step150). The extruded metal continues to flow until it gradually fills the die channel(step200) and finally accumulated on each other and compressed to get back to the original shape of the rod (step 439). In this manner, a severe plastic deformation has been achieved to change mechanical properties and microstructure without changing the rod shape. From the strain distribution, maximum strain is observed at the die throat and the ends of the rod, as seen Fig.9, because of high reduction ratio and
contact friction. Whereas at the ends of the rod there was a small distortion occurred due to excessive compression. At the last step (step 439), It is obvious the extruded rod is smooth, and there is no change in its cross-section along the extruded length of the rod.

![Figure 9. Equivalent strains of one-pass CEE at different steps](image)

![Figure 10. Variation of total equivalent strain values over rod cross-sectional area at sections A-A and B-B.](image)

Figure 10 shows a variation of total equivalent strain values along the radial distance from the center of cross-section of the rod at sections A-A and B-B after one pass and two passes as calculated from FE-simulation results. It is obvious that a homogenous equivalent strain profile is achieved through the cross-section of the rod despite slight increase near the outer surface of the rod. However, the slight increase (inhomogeneity) in strain values near the outer surface of the sample might be due to redundant and friction
strain at the interface between die and specimen. Also, as it is seen, the equivalent strain has significantly increased and doubled after pass two. Due excessive deformation at the deformation zone, the effective strain shows high values for passes one and two at section B-B whereas it has lower values at section A-A.

4.5.2 Damage

Damage closely relates to the likelihood of ductile fracture in a deformed part. The ductile damage cumulating process for Al-1%Cu alloy was evaluated according to the Cockcroft & Latham damage criterion. The damage factor D was used to predict fracture in cold forming operations. The variation of damage value based on the Cockcroft and Latham criterion along section (A-A) and (B-B) at the specimen for 1pass and two passes has been calculated and shown in the Fig. 11. In the typical material of Al-1%Cu alloy, the maximum damage value appears near the surface of the rod corresponding to higher effective train as shown in Fig. (10), while the damage value D, appears to be homogenous near the rod center. So, the crack initialization will necessarily occur at the surface of the workpiece if the damage value D reaches a critical value (say D > 0.9).

For one and two passes, damage values at cross-sectional area Sec (A-A) are close to each other despite some deviations near the outer surface of the rod. Also, it is noticed that the material at cross-section B-B (extrusion channel II) experiences more damage at one pass than in two pass then the two curves begin to decline towards the outer surface of the rod. This is because of the combined action of severe compression resulted from plunger back pressure and punch extrusion load. The simulation results confirmed that the damage value is affected by the number of passes and the processed material is safe since the damage value D does not exceed 0.5.

![Damage distribution at 1st and 2nd passes of CEC process.](image)

**Figure 11.** The damage distribution at 1\textsuperscript{st} and 2\textsuperscript{nd} passes of CEC process.

4.5.3 Load-stroke

Fig. 12 shows the load–stroke curves for punch and plunger in one and two passes. After one pass of CEC (see Fig. 12(a)), the punch load increases gradually from zero displacements up to 19 mm while the back pressure (BP) is zero. The workpiece material
goes out from the extrusion zone, is not subjected to frictional, force or geometrical constraint. So it passes freely without additional deformation until it touches the upper part of the stationary plunger. At that time the back pressure starts to increase and resist the material from further axial deformation. Consequently, the punch load increases with increasing BP because the amount of BP is added to the processing load. So, as the BP increase, the processing load increase till the two curves come closely to each other. As known, the back pressure (BP) plays a crucial role in minimizing or eliminating defects, i.e.; surface cracking appeared on the surface of the workpiece in the CEC processing. Therefore the damage value does not exceed 0.5 (always below unity as shown in Fig.11) which ensure no existence of fracture or material failure take place during the CEC process. After two passes of CEC (Fig.12(b)), the punch load increased approximately to $4 \times 10^5$N despite the fluctuations on the curve then it remains stationary until the extruded rod faced the plunger and as a result, the punch load increased sharply when PB applied simultaneously. This may be because of the material in the first pass has exposed to strain hardening which affecting its hardening behavior in the second deformation pass and consequently load curves. Also, the friction load of due to the interaction of the workpiece with the surface of die channel during the extrusion process is added to the processing load. The internal friction (redundant work) due non-honorees deformation is another factor that contributes to the increase in the overall punch load.

![Figure 12. The load stroke curves for punch and plunger at: (a) 1 pass, (b) 2 passes of CEC process.](image)

5 Conclusion

In this paper, a simple CEC die was designed and manufactured to apply sever plastic deformation (SPD) on cylindrical specimens. Al-1%Cu alloy was used as a testing material and subjected to two passes of CEC. The deformation behavior of the processed material was simulated using Deform 3D finite element software. The results were concluded in the following points:

1. Two passes of simple cyclic extrusion are sufficient to produce dynamic recrystallization that refined the grain size from $\sim 1500 \mu m$ to $100 \mu m$. 
(2) After two passes of SCEC the ultimate tensile strength and elongation% were significantly improved by 145% and 191%, respectively. While the hardness was significantly improved by 49%.

(3) Fractography analysis, showed that the fracture mode after two passes SCEC was a mixed type fracture with the features of cleavage and dimple.

(4) Damage and equivalent plastic strain distributions have proved the possibility of the proposed SCEC technique to achieve severe plastic deformation due to accumulated shear strain.

Further studies and experiments are needed for a better understanding of the deformation behavior under different processing conditions.

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