Wear behavior of Al-6061 alloy processed via cyclic extrusion compression (CEC)

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1- Abstract

A recently developed severe plastic deformation technique, cyclic extrusion–compression (CEC), was applied on Aluminum alloy 6061 to investigate the effect of CEC process on the mechanical properties and wear behavior. The samples were processed by CEC up to 6 cycles with a strain of 0.62 per cycle at room temperature, followed by dry sliding wear test using pin-on-disc machine under different time 5, 10, 15, 25, 35 minutes and constant load and speed 5N and 150 rpm respectively. The effect of time, load, speed and CEC number of cycles on the microstructure, hardness, and wear behavior including CEC, the weight loss and coefficient of friction have been investigated. Severely deformed specimens exhibited better wear resistance due to the formation of very fine grains and the increase of the specimen hardness during the CEC deformation process. After the wear test the surface of worn specimens was investigated by scanning electron microscope (SEM) and EDX analysis.

Keywords: Wear, Severe plastic deformation (SPD), Cyclic Extrusion Compression (CEC), AA6061 aluminum alloy, SEM (scanning electron microscope), EDX analysis.

2- Introduction

Interest in the processing of bulk ultrafine-grained materials through the application of severe plastic deformation has grown significantly over the last decade; numbers of techniques have been developed for refining the structure of metals and alloys by severe plastic deformation (SPD). These deformation processes such as high Pressure Torsion (HPT), Equal Channel Angular Pressing (ECAP), Cyclic Channel Die Compression (CCDC) and Cyclic Extrusion

Compression (CEC), achieve grain refinement in the metal through the introduction of large strain. The accumulated energy of deformation aids in the formation of ultra fine grains in a continuous recrystallization process [1-3].

A unique feature of SPD processing is that the high strain is imposed without any significant change in the overall dimensions of the workpiece compared with the other conventional deformation processes [4-7]. A number of investigations reported that the improvement of the mechanical properties like hardness, ultimate tensile and yield strength resulting from the creation of fine grained structure with high dislocation density formed due the large applied strain is reflected on the wear behavior [8-9].

The objective of the present investigation is to study the tribological properties of Al-6061 alloys processed by Cyclic Extrusion Compression (CEC). For this purpose dry sliding wear tests have been conducted using a pin-on-disk machine under different times, constant load and speed. The worn surfaces of the specimens were investigated by optical microscopy, SEM and EDX analysis.

3- Experimental procedure

3.1 CEC sample preparation

Cast billets of AA6061 aluminum alloys with nominal chemical composition showed in table (1) were received from Egypt Aluminum Company. The billets were machined to diameter of 14 mm and length of 50 mm, and then annealed at 425C° for 3 hrs. followed by furnace cooling. Fig. 1 illustrates the assembly solid modeling of the cyclic extrusion compression device.

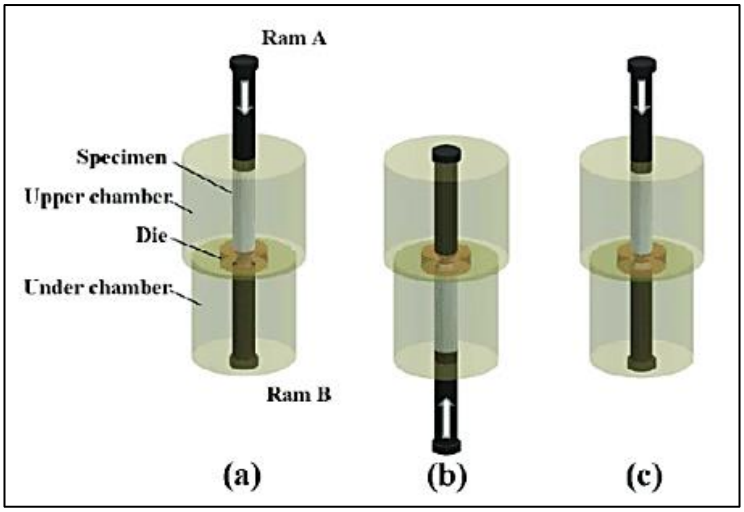


Fig.1 Schematic diagram of assembly solid modeling of the cyclic extrusion compression device

The prepared billet with 14 mm diameter was extruded through the CEC die to obtain an extruded diameter 12mm. This was followed by compression process to the original diameter 14 mm to complete the CEC cycle and achieve total strain of 0.62/cycle according to Eq.1. Fig. 2 shows a picture of a sample during CEC and sectional drawing of the constructed CEC split die.

$$\varepsilon = 4n \ln\left(\frac{D}{d}\right) \qquad \text{Eq.1 [2]}$$

Where: n: number of deformation cycles, D: initial diameter, d: extruded diameter

Table 1. Chemical composition wt% of Aluminum alloy 6061

Mg	Si	Fe	Cu	Cr	Mn	Zn	Ti	Al
0.9	0.62	0.33	0.28	0.17	0.06	0.02	0.02	Rest

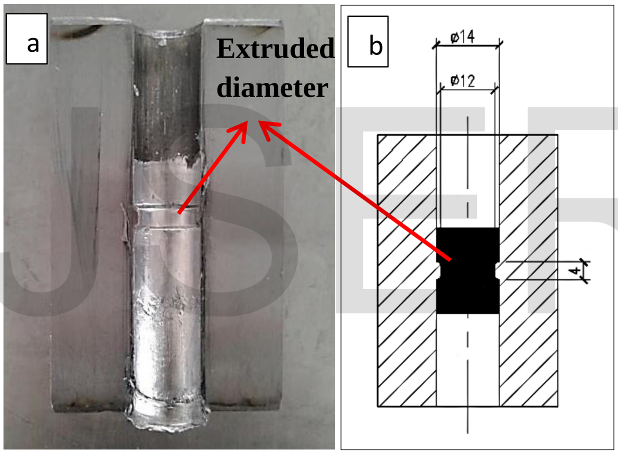


Fig.2 picture of sample after the process is given in (a) and a longitudinal sectional drawing of the CEC split die (b).

3.2 Wear test

Wear test was carried out on a pin-on-disk model TE 97 multi-Axis tribometer model, shown in Fig.3. The tests were performed according to ASTM G99 and DIN50 324 using a 150 mm diameter disk with HRC 61-64 hardness. Prior to the wear test the specimens were machined to 20 mm in length and 8 mm in diameter. All the specimens were ground by emery papers 1200 grit and cleaned with acetone before doing the test. The tests were conducted under constant load of 5 N at a fixed sliding speed of 150 rpm. The samples weight was measured every 5, 10, 15, 25 and 35 minutes using Sartorius scales balance model (BP 310S) with accuracy 0.1mg. The wear rate was calculated by dividing the weight loss per traveled distance.

Fig.3 pin-on-disk TE 97 multi-Axis tribometer wear test

3.3 Metallographic examination and hardness test

In order to analyze the initial condition and refined microstructure after CEC cycles; samples were sectioned longitudinally. The metallographic analysis was made using the optical microscope (Zeiss) for both the annealed and the deformed specimens after 6 cycles. After the wear test the topography for the worn surfaces was examined using a scanning electron microscope (SEM) Model Quanta 250 FEG (Field Emission Gun).and, (Energy Dispersive X-ray Analyses) (EDX), with accelerating voltage 20 KV. Macrohardness profiles were performed on the internal plane using a load of 5 kg by 20 s. On each specimen 7 measurements were performed at various distances below the surface in order to obtain representative average hardness value.

4- Results and discussion

4.1 Metallographic examination

Fig. 4-shows the evolution of the grain structure for Al alloy 6061 (as-received) annealed condition. The microstructure consists of dendritic coarse equiaxed grains with average grain size 250 µm. After 6 cycles CEC the deformed grains were finer with average grain size about 25 µm and elongated in the extrusion direction, as indicated by the arrows direction in Fig.4-b. This indicates the large decrease in the average grain size with CEC processing cycles, Fig. 5. These results are consistent with the results obtained on AlMgSi alloy [11], 6061 aluminum alloy [12], and ZK60 Magnesium Alloy [13].

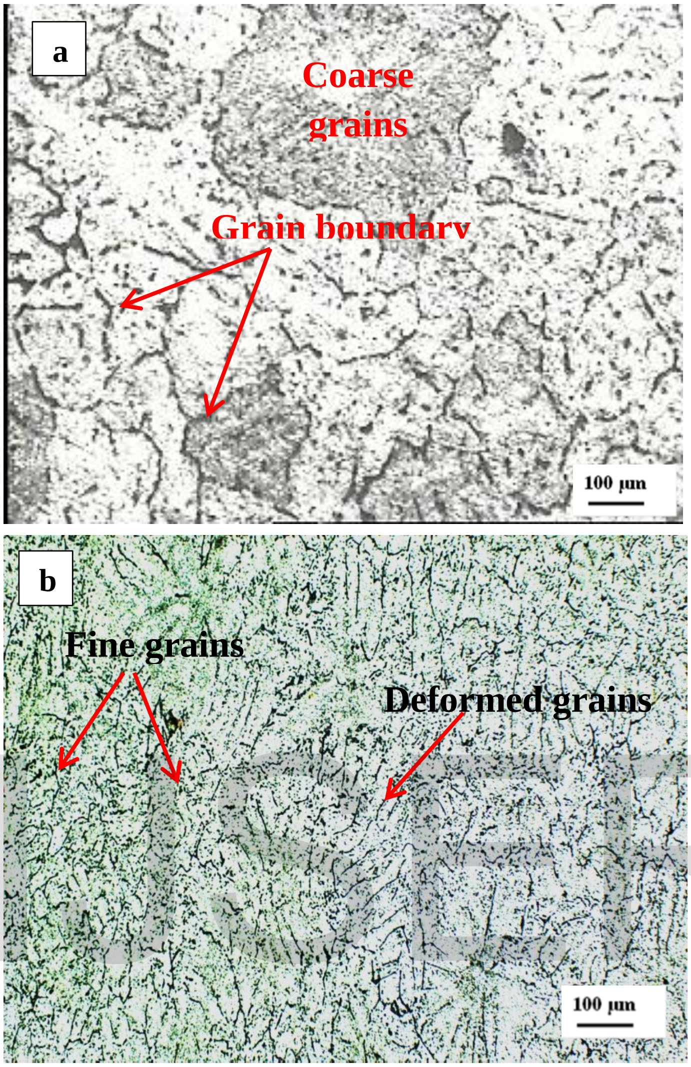


Fig. 4 Optical microstructure for Al/alloy 6061 in (a) annealed and (b) after 6 cycle CEC

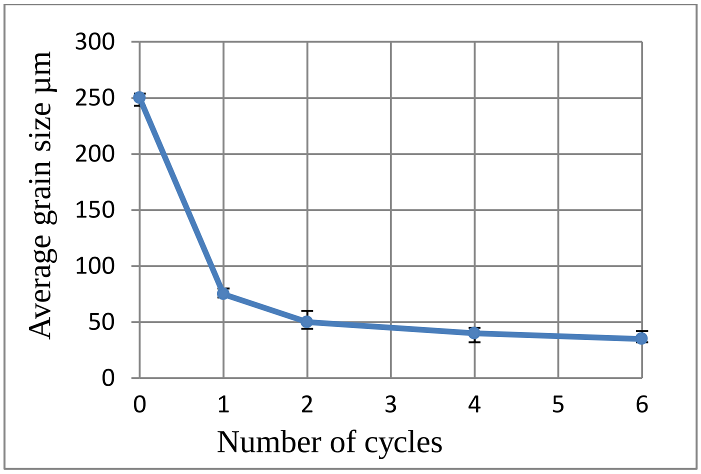


Fig. 5 Average grain size of Al/alloy 6061 for initial condition and after each CEC cycles

Fig. 6 also illustrates the increase in hardness with increasing number of cycles. It is observed that the fine grained materials produced by CEC deformation process exhibit high hardness value. It has also been observed that as grain size is reduced from 250µm to 25µm average grain size by 90%, the hardness typically increases from 29 Hv to 56 Hv by 52%. The relationship between the hardness value and the inverse square root of the average grain size is shown in Fig.7. The results agreement the process material obeyed the Hall–Petch relationship, that is, hardness typically increases with decreasing grain size.

The Hall–Petch equation expresses the grain size dependence K is the Hall–Petch slope and D is the grain diameter.

$$H_O=H_1+K/\sqrt{D} \qquad \text{Eq.2 [4]}$$

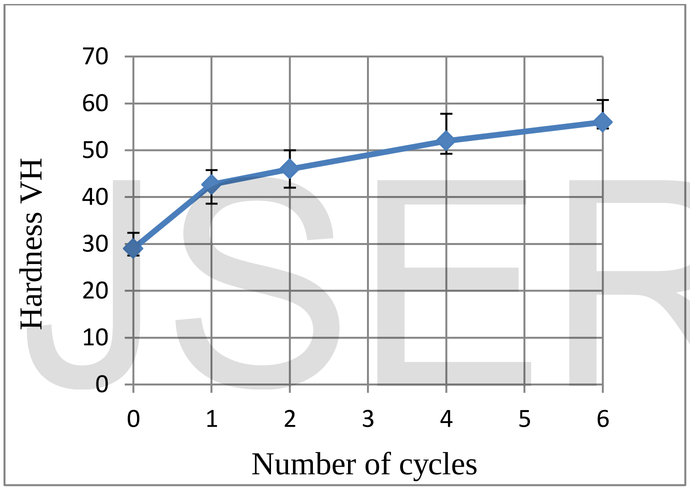


Fig. 6 Hardness of Al/alloy 6061 for initial condition and after each CEC cycles

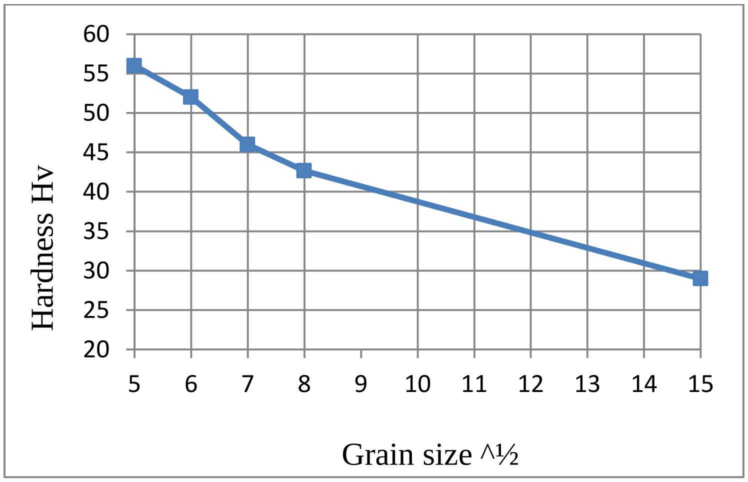


Fig.7 The relationship between the hardness value and the inverse square root of the average grain size of processed Aluminum alloy 6061at room temperature

4.2 Wear properties

The effect of time and the number of cycles of (CEC) process on the wear weight loss during wear test after 5, 10, 15, 25 and 35 minutes, Fig.8, shows that the weight loss increases in general with time for all conditions and that the effect of cycles start to be noticeable beyond 10 minutes. After 35 minutes of wear test, it is found that the more cycles applied on the material, the lower the weight loss as represented in Fig.9.

The results of the wear rate of annealed samples versus CEC cycled samples are represented in Fig.10, for different wear times. The relation between the wear rate and CEC cycles at constant load, speed and at time 35 minutes, in Fig.11, indicates a reduction in wear rate by 22%, 31% and 46% at two, four, and six cycles of the CEC process as compared to the initial annealed condition. This behavior can be explained by the grain refinement and the increase in the hardness due to the cold working of processed materials.

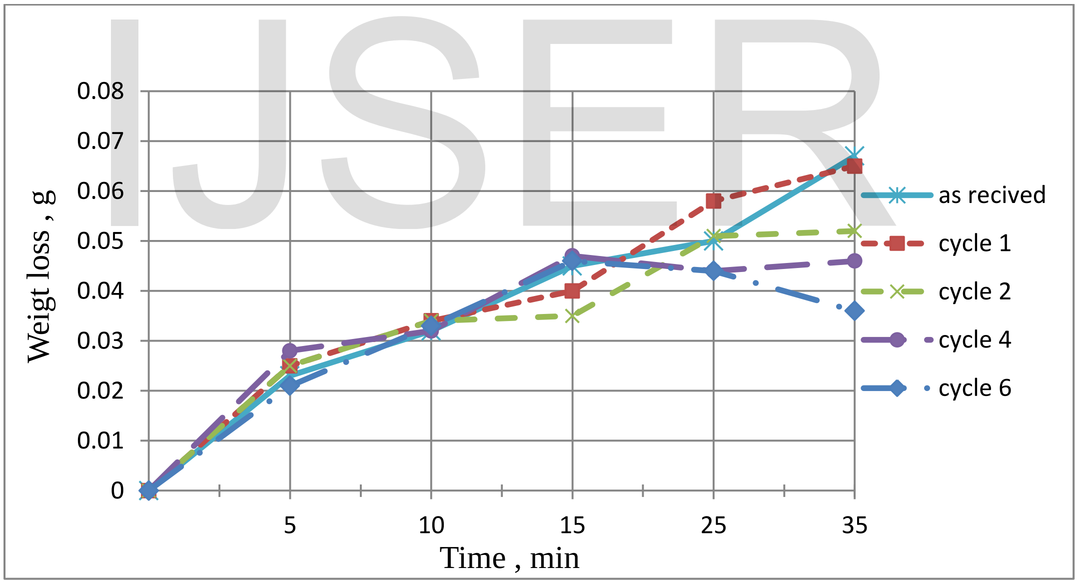


Fig.8 Effect of CEC cycles and time on the wear mass loss of Al-6061 under constant load 5N and speed 150 rpm

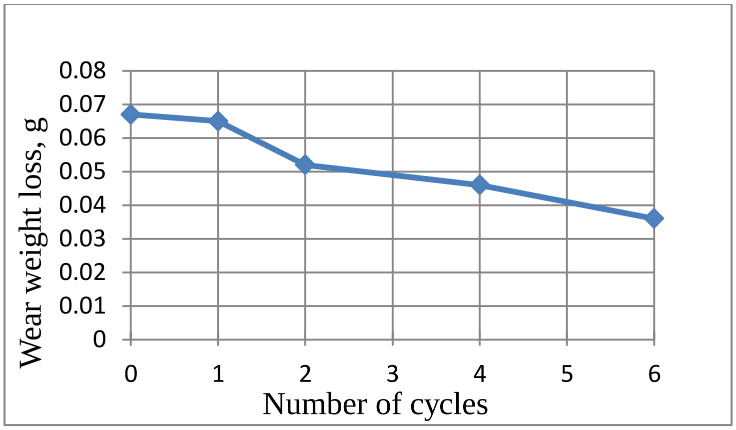


Fig.9 Effect of number of cycles CEC cycles on the wear weight loss of Al-6061 under constant, load 5 N and time 35 min

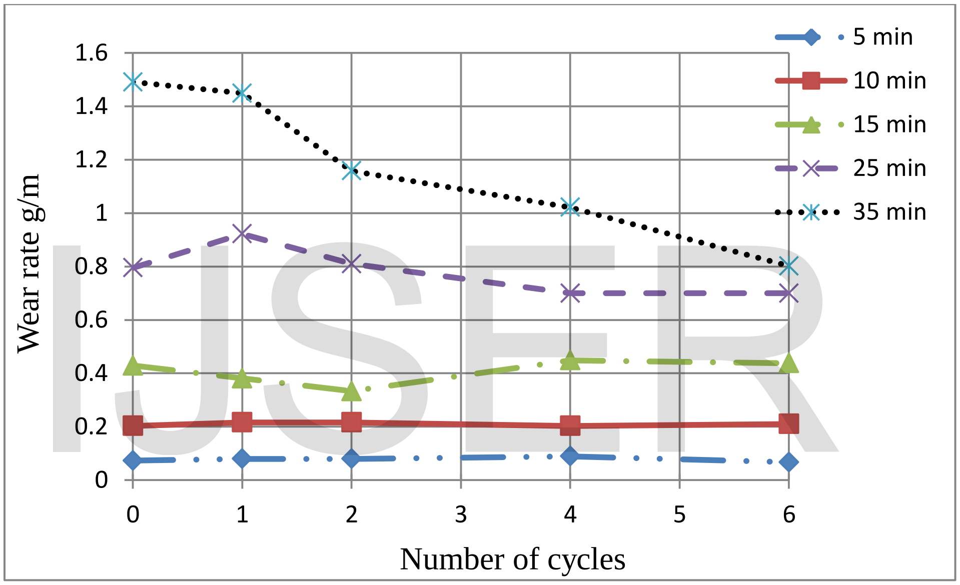


Fig. 10 The wear rate of Al/alloy 6061 before and after the CEC process up to 6 cycles.

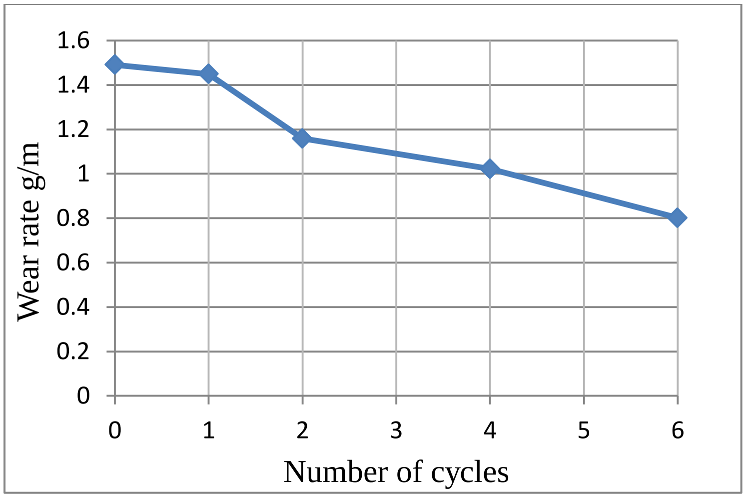


Fig. 11 The wear rate of Al/alloy 6061 before and after the CEC process up to 6 cycles at 35 min

Fig. 12 represents the effect of hardness on wear rate for the first, second, fourth and sixth cycles of the CEC process. A linear trend line is found for the plotted data points. Results show that there is a linear correlation between the hardness and wear rate. The linear relationship also can be a quick way to estimate the wear rate of the aluminum alloy 6061after the different CEC cycle numbers. Using the corresponding equation

$$\text{Wear rate} = 0.082\ Hv + 72.307 \qquad \text{eq.3}$$

The increase of wear behavior as well as hardness behavior after the CEC process can be associated with the cold working and the grain refinement of aluminum alloy.

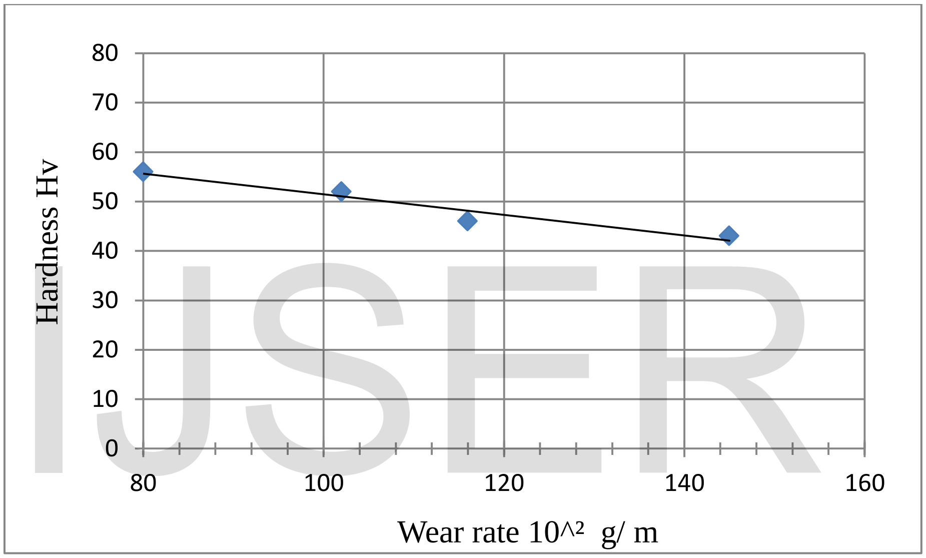


Fig. 12 Linear fitting of experimental wear rate and hardness of aluminum alloy 6061 before and after the CEC process up to 6 cycles.

Fig. 13 represents the relation between the friction coefficient and the number of cycles of processed alloy with the wear time, and at constant time 35 minutes in Fig. 14. It was found that average friction coefficient of aluminum alloy which is about 1.94 at the annealed condition, reached 1.73 after 6 cycles with about 12% reduction. This reduction of friction coefficient during the CEC process may be attributed to the increase of hardness. The same trend at the reduction of friction coefficient by imposing intensive plastic strain has already been reported previously [14-15]. The lower coefficient of friction can be reflected on lower heat generated during service.

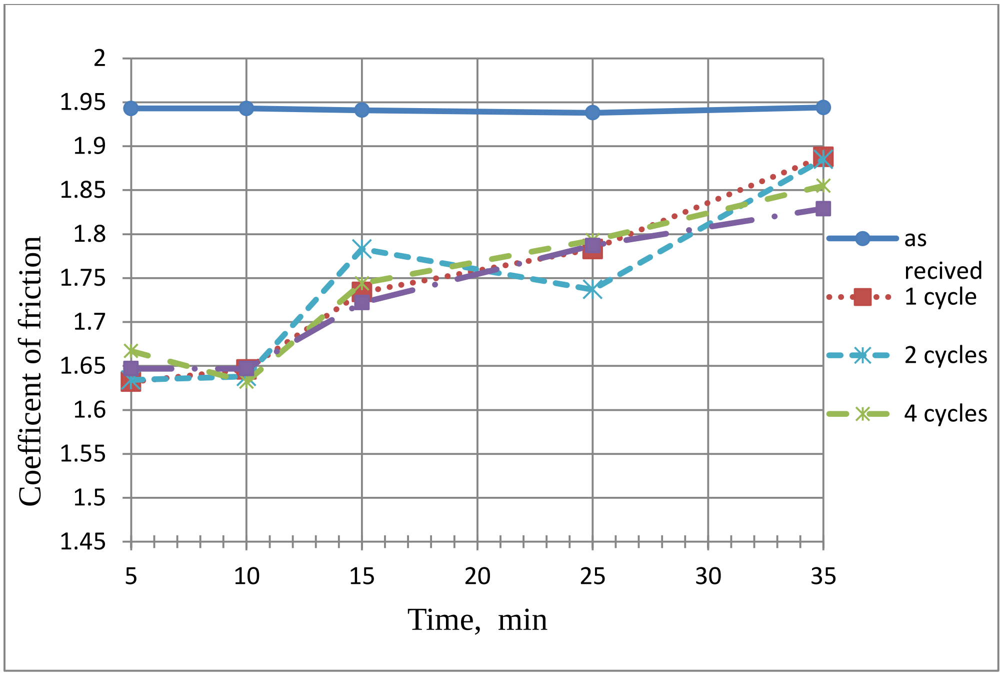


Fig. 13 The effect of time on the friction coefficients for annealed and CEC up to 6 cycles specimen

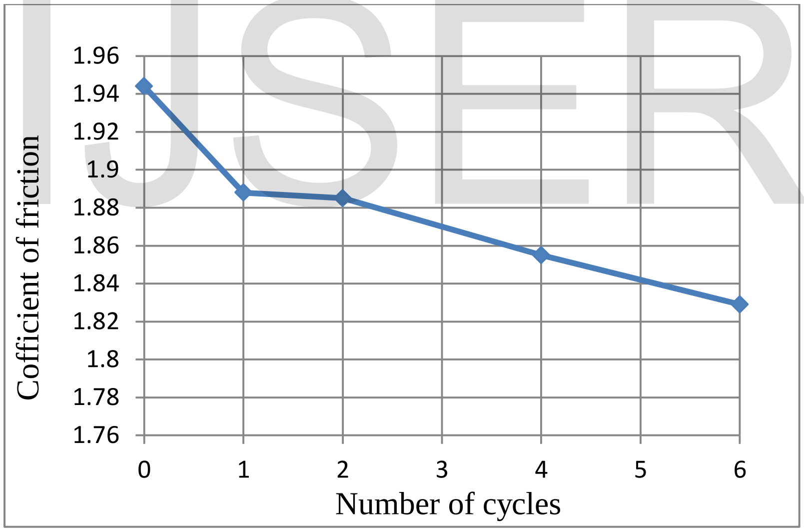


Fig. 14 The effect of time on the friction coefficients for annealed and CEC up to 6 cycles at time 35 min

4.3 Worn surface morphology

Investigation of the worn surface was made on the annealed specimen using SEM after wear test condition for 35 minutes Fig.15. As shown in Fig.15 (a-b) deep grooves aligned in the sliding direction indicates a severe plastic deformation due to abrasive wear mechanism. Metal fragments or broken particles - resulting from plastic deformation and fracture of the contacting asperities of the two surfaces - are produced and act as abrasive particles during sliding. These broken particles leave the surface causing void formation as observed in the magnified view in Fig 15 (b). EDX analysis for the annealed worn surface shown in Fig.16 shows only the presence of Al, Mg and Si, which are the Al alloy elements with no contamination from the wear disc. Considering the worn surface of CEC sample after 6 cycles, Fig.17 (a, b), fine grooves aligned in the sliding direction indicate abrasive wear mechanism. EDX analysis reveals the presence of Fe due to the transfer of Fe from the steel disc to the specimen, Fig.18. These results are due to the higher hardness of the $\mathrm{CEC_{ed}}$ samples compared with the annealed ones, indicating that CEC process leads to less surface damage, less surface debris and minor width of wear grooves. The results are in agreement with pervious work [16-17].

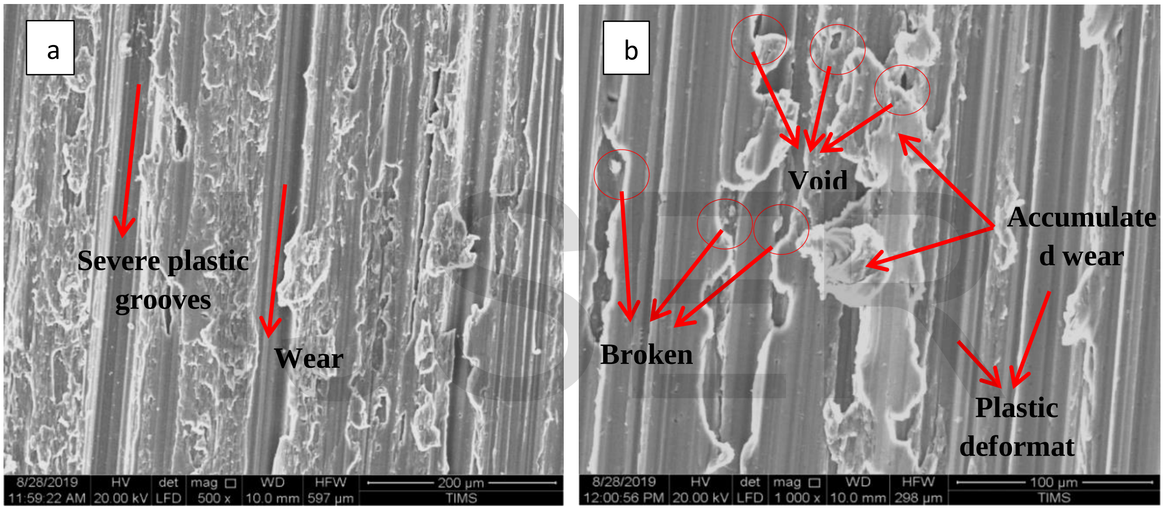
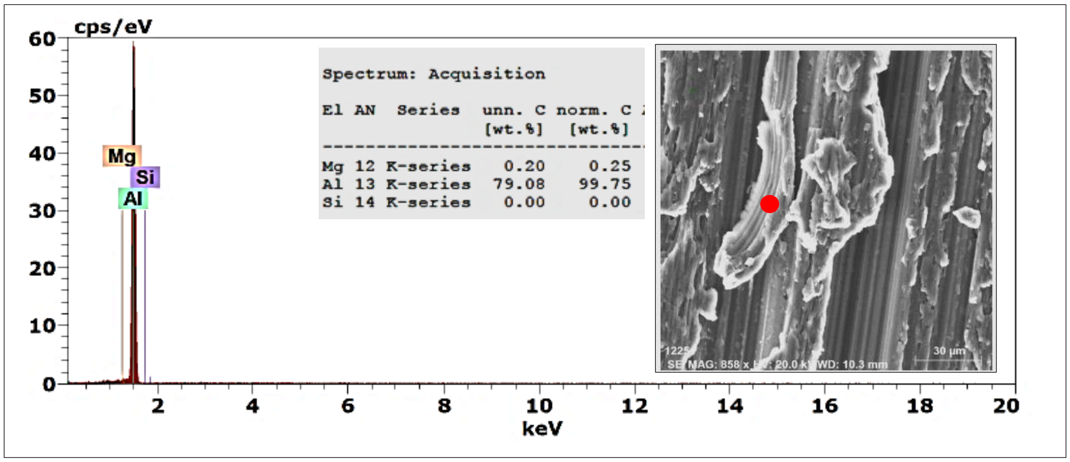


Fig.15 SEM image of the wear surface of annealed specimen of Al/alloy 6061 at applied load of 5N and sliding speed of 150 rpm at 35 min.



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Spectrum: Acquisition

El AN  Series   unn. C norm. C
                [wt.%]  [wt.%]
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Mg 12 K-series   0.20    0.25
Al 13 K-series  79.08   99.75
Si 14 K-series   0.00    0.00
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Fig. 16 EDX spectrum of annealed specimen of Al/alloy 6061

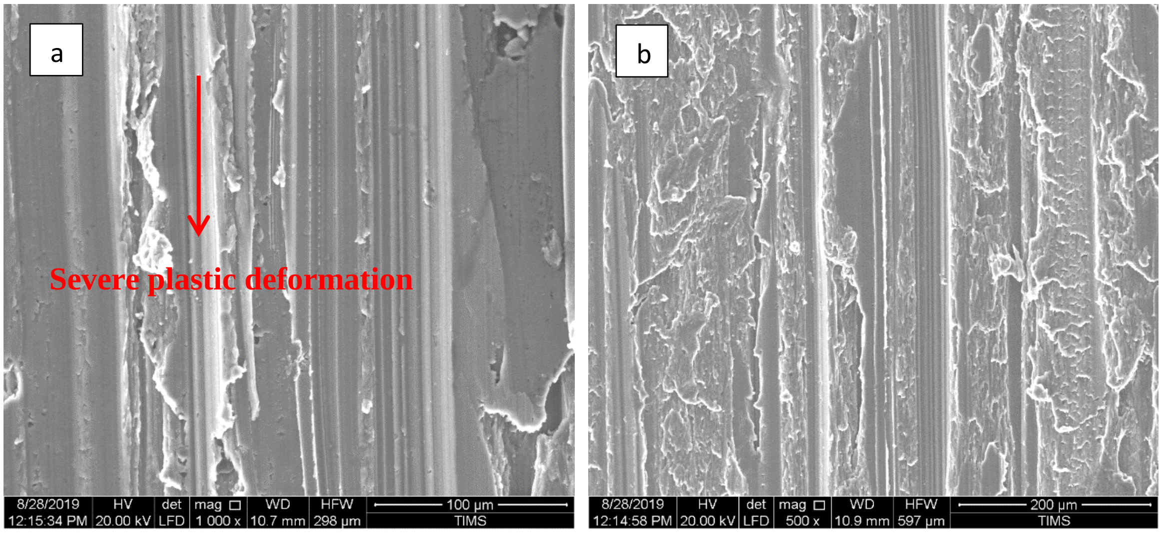
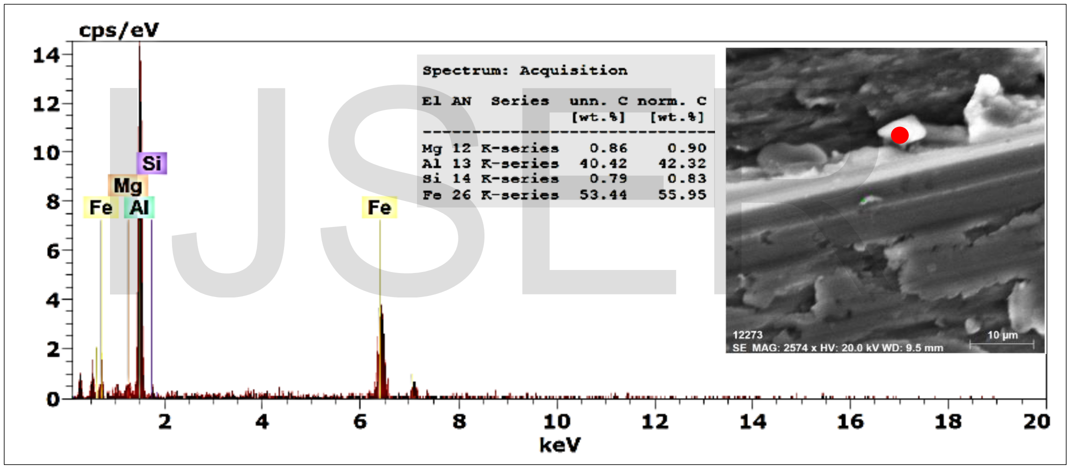


Fig. 17 SEM image of the wear surface of 6 cycles (CEC) specimen of Al/alloy 6061 at applied load of 5N and sliding speed of 150 rpm at 35 min



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Spectrum: Acquisition

El AN  Series   unn. C norm. C
                [wt.%]  [wt.%]
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Mg 12 K-series   0.86    0.90
Al 13 K-series  40.42   42.32
Si 14 K-series   0.79    0.83
Fe 26 K-series  53.44   55.95
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Fig.18 EDX spectrum of the wear surface of 6 cycles (CEC) specimen of Al/alloy 6061

5- Conclusions and Summary

The wear properties of Al 6061 alloy processed by CEC up to 6 cycles were investigated by means of pin-on-disc dry sliding test under various times.

a. Wear test results show that the wear resistance of Al-6061 alloy was improved significantly by refining the grain size of the alloy during CEC process due to increased hardness and of the alloy.

b. It is also apparent from sliding wear test that weight loss increases with increasing the test time for all conditions of wear test.

c. The wear rate decreased by increasing the number of CEC cycles comparing with the annealed condition by 46%, but there are about 12% reductions at the average friction coefficient by utilization of 6 cycles of the CEC process.

d. A hardness and wear rate linear relation is proposed as a simple and quick way to estimate the wear rate of the aluminum alloy after the different CEC cycle.

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