Improving Surface Texture by Investigating the Influence of Number of Passes and Cutting Conditions in Face Turning Process for Pure Copper Produced by ECAP

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Abstract-- Due to the surface texture and dimensional accuracy comes to be extremely necessary for the designer or producer of machine tools, along with the user. The main objective of this work is to investigate the influence of a number of passes and machining cutting conditions on the surface texture of commercially pure copper produced by the ECAP process. In this research, the X-ray diffraction (XRD) test will be used for examining the structure of the pure copper sample and the produced samples by the ECAP process. Also, the features of the microstructure of the original sample and the ECAP samples will be investigated by utilizing the scanning electron microscopy (SEM). Then, the surface texture of the machined samples will be studied by using a 3D optical microscope and SEM device at different machining cutting conditions. Finally, the experimental results are displayed that the increase in the number of the ECAP passes had much affected the surface topography of the machined sample.

Index Term-- Surface roughness; ECAP; Number of passes; Machining cutting conditions; XRD; SEM.

1. INTRODUCTION

The current trend is to produce nanostructure materials due to its high strength values. In the past two decades, equal channel angular pressing (ECAP) technique becomes the commonly utilized technique to produce nano-structure materials (ultrafine grained structure). Due to new advancements in electronics technology, the need for a material with higher strength and higher electrical conductivity is increased. The copper alloys are the commonly used materials for these purposes. The electrical conductivity of the copper alloys is smaller than the pure copper. The use of nanostructure commercial pure copper produced by ECAP is the best choice to overcome this issue [1].

Severe plastic deformation (SPD) methods are a group of methods where severe strain is made in the material without varying the whole sizes. This method permits manufacturing materials with a very fine grain structure. The equal channel angular pressing (ECAP) technique is a novel process utilized for the manufacture of ultrafine grained structures with high advantageous mechanical and physical properties. In this technique, the sample passes a die which has a channel with a precise angle of curvature. Throughout the passage of material from the curvature of the mold, high shear strain take place in the material. Subsequently, the cross-section leftovers constant and the strain is kept inside the material, grain boundaries diverge and the material develops fine grained [2]–[7].

In ECAP process, when it concerns to the homogeneity and the size of the added strain, this optimum form of minimum deformation zone can be achieved utilizing a die with internal channel shape identified by an angle of (90°), the minimum friction between the specimen and the die wall, and the existence of a sharp external corner of the die. The lack of a sharp corner has a similar influence as that of higher friction, that is, expansion of the minimum deformation zone and/or raise in the heterogeneity of the added strain [8].

Frequent extrusion of the samples through the ECAP die produced a steady deformation of an ultra fine grain structure. The production of this structure is influenced by the motivation of many slip arrangements through separate extrusions. This is produced by the rotation of the sample between ECAP passes. The changes in the route of rotation produce four diverse categories of extrusion of the sample through the ECAP channel; these are named the formation routes. The fundamental, defined formation routes are category A, category Bα, category Bc, and category C. The formation route “A” establishes the sample without any following rotation between the ECAP passes; the formation route “Bα” the direction varies every time (±90°); in route “Bc,” depends on rotating the sample at (90°) between the individual ECAP passes, Finally, route “C,” rotates the sample at (180°) between the individual ECAP passes [9]; as shown in Figure1.
Rifai et al. showed that the use of deformation route “C” between the individual ECAP passes leads to uniform microstructure and an increase in corrosion resistance [11]. Graiger et al. investigated the microstructure of samples of copper produced by the ECAP method for eight passes. They perceived that the average grain size is reformed from 50 μm as an initial value to 5 μm after pass number eight in copper samples fabricated by the ECAP process [12].

Morehead et al. produced the ECAP samples form electrolytic tough pitch copper to produce ultrafine grain microstructure at room temperature. Marta and his assistants compare microstructure and changes in a broad range of properties for the ECAP sample with the original samples by using the electron backscatter diffraction for both cases and the transmission electron microscopy for the ECAP samples only. They tried to relate the microstructure with the outcomes of tensile tests, electrical conductivity measurements electrochemical tests, and thermal stability up to 200 °C. They establish that the refine grains microstructure has a 50% increase in the mechanical properties (ultimate tensile strength and yield strength). On the other hand, the refined grains microstructure is caused by a reduced in electrical conductivity and thermal stability by 7%, and 12.5% respectively. Also, they got decreasing in microhardness of more than 10% [13].

Guo et al. utilized a die with an internal angle (Φ) =105° and an outer curvature angle (ψ) =57° to make the ECAP deformation process by route Bc. Guo and coworkers studied the deformation manners of single crystal copper through the ECAP process by using the X-ray diffraction (XRD), the electron backscatter diffraction (EBSD), and the optical microscope (OM). They examine the mechanical properties and the electrical conductivity for the produced sample by the ECAP process. They found that by increasing the number of ECAP passes, the mechanical properties are increased while the electrical conductivity and the plasticity remain the same [14].

Zhang et al. utilized a high-velocity equal channel angular pressing (ECAP) tool to produce the ultrafine grain sample of pure copper with excellent distribution of grain size in a sample volume. Zhang and coworkers studied the microstructure and mechanical properties for the ECAP samples. They got the ECAP sample with better-refined grains during three passes of the ECAP process. Also, they observed that the tensile strength is raised to 187% larger than the annealed rod. Finally, they found that the micro-hardness is enhanced after the first three passes, but then it stopped after that [15].

The machining of metal is probably the most significant manufacturing operations in the area of material removal [16]. The basic target of the metal cutting science is the solving of workpiece issues associated with the efficient and accurate removal of metal from the workpiece. The main objective of performing machining investigation is to find out the interaction between the machining tool and the workpiece material that the machining costs can be reduced with enhancing the surface quality of the workpiece [17]. Machinability is the scale for how effectively these materials can be machined utilizing the suitable machining tool and machining cutting conditions [18].

Krallics et al. investigated the effect of passes number for AA6082 (Al-Mg-Si) samples produced by the ECAP process (route C) on its strength and its ductility. They found out that after four passes the strength was increased while the ductility was decreased. After eight passes, they observed that the strength was still the same at four passes while the ductility was extensively increased. Also, they studied the effect of passes number for ECAP samples on the surface quality of the samples for turning machining process. They discover that the samples after eight passes have the surface quality better than the surface quality for the original material at the same machining conditions [19].

Morehead et al. researched the machinability for the pure copper samples fabricated by the ECAP technology utilizing...
two different materials cutting tools (tungsten carbide, and polycrystalline diamond). They established that polycrystalline diamond is preferred to machine ultrafine grain copper samples. Because of it has significantly better wear resistance, provided smaller cutting forces, and produced a significantly better workpiece surface finish [20].

Horvath and Dregelyi-Kiss presented research for the turning operation of an (Al-Mg-Si) alloy with a chemical vapor deposition diamond tool by using the design of experiments. An empirical equation was formulated to connect between the surface roughness and the cutting conditions. This equation was helpful in calculating the average surface roughness for the studied range of the optimal machining conditions. They established that the feed rate is more effective than cutting speed on the surface roughness [21].

Rouhizadeh et al. studied the influence of the electrical discharge machining (EDM) process parameters on the workpieces surface roughness when using the tool of pure copper fabricated by ECAP for four and eight numbers of passes. The final results presented that ECAP copper tools with four passes are decreased the workpiece surface roughness. On the other hand, at the same EDM parameters, the ECAP copper tools with eight passes are increased the workpiece surface roughness [22].

Kumar and Chauhan studied the influence of cutting conditions (feed rate, cutting speed, and approach angle) on the surface quality for Al7075 composites in turning operation. They utilized the response surface method and the artificial neural networking for this investigation. They pointed out that the feed rate is more affected than cutting speed and approach angle on the surface quality of Al7075 composites materials [23].

Mahdieh and Reisabadi investigated the influence of the electro discharge machining process on the coarse grain copper (copper alloy) samples produced by the ECAP deformation method. Mohammad and Sara compared between the coarse grain copper samples and the ultrafine grain samples produced by the ECAP deformation process. They used optical microscopy, scanning electron microscopy and microhardness tester to study the process parameters for the electro discharge machined samples (heat affected zone, and the thickness of the recast layer) in addition to the cracks density and the micro-hardness. They figure out that the ECAP samples have thicker heat affected zone and recast layer with higher cracks density, comparing to the original samples. On the other hand, the micro-hardness of the electro discharge machined surface for the original samples and the ECAP samples are almost the same [24].

For samples of solid state recycled 6061 aluminum chips fabricated finally by ECAP process to increase its strength, Abbas et al. investigated the influence of machining parameter (cutting speed, depth of cut, and feed rate) on the surface texture during the dry turning process. They utilized the response surface method (RMS) and the mathematical model to adjust the machining parameters for the high-quality surface finish. They found out that the surface texture improved by increasing the number of passes for the final samples which are produced by the ECAP technique. Finally, they established that the feed rate is the most effective machining parameters on the surface texture of the studied samples [25].

The main objective of this work is to investigate the effect of a number of passes and machining cutting conditions on the surface roughness of commercially pure copper produced by the ECAP process. To achieve this objective, the four passes ECAP samples will be machining by face turning operation at divers cutting conditions. Then, Bruker 3D Optical Microscope is used to measure the surface roughness for the machined ECAP samples for all passes in the ECAP process at different machining cutting conditions. Finally, the samples will be examined for their microstructure after the ECAP process and their surface texture after the machining process by using x-ray diffraction (XRD), and scan electron microscope (SEM).

2. RESEARCH METHODOLOGY

The commercial pure copper produced by the ECAP process is a nano-structure material (ultrafine grained structure material). This novel material has higher strength and higher electrical conductivity than in the pure copper material. The current research project focuses on the investigation of the surface quality of the machining pure commercial copper produced by the ECAP process at different passes and different cutting conditions.

The research will be conducted in five main phases. In the first phase, 40 samples of commercially pure copper with dimensions of (21.8 mm in diameters and 140 mm in height) will be cut and used for the ECAP process. Through this phase will be used an ECAP die made from Steel-H13 with a 90° channel, as shown in Figure 2. Four passes of ECAP (route C) samples are fabricated by utilizing a 1600 KN hydraulic press. Through the ECAP passes, MoS2 lubricant was utilized to decrease the friction between the samples and die walls. Small plungers of Steel-H13 with 20 mm in diameter and 25 mm in length are utilized to push the sample along the channel of the die. The samples are fabricated at room temperature with a punch speed of 2 mm/sec. The cylindrical samples for each ECAP passes will be cut to dimensions of 20 mm in diameter and 20 mm in height utilizing a wire cutting machine to avoid the changes in microstructure.

In the second phase, X-ray diffraction (XRD) will be utilized for examining the structure of pure copper and the ECAP samples to determine the phases present. The features of the microstructure of the ECAP samples will be investigated by utilizing the scanning electron microscopy (SEM).

In the third phase, the four passes ECAP copper samples are machined by using face turning operation at divers machining cutting conditions (cutting speed, feed rate, and depth of cut); explained in Table 1. In this phase, the Taguchi
technique (robust design method) will be developed to optimize the machining cutting conditions and enhance the quality of samples that are manufactured. Figure 3 shows the experimental setup for the face turning process on the conventional lathe.

In the fourth phase, the effect of machining cutting conditions on the surface roughness of the machined ECAP samples at a different number of passes will be investigated by using Bruker 3D Optical Microscope to measure the surface roughness of the machined ECAP copper samples, as displayed in Figure 4.

In the final phase, scanning electron microscopy (SEM) will be used to analyze the surface texture for all machined ECAP samples at different machining cutting conditions. Figure 5 presents the flow chart of the research methodology.

Fig. 2. Equal Channel Angular Extrusion (ECAP) Die.

Table I

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Sample No.</th>
<th>Feed rate (mm/rev)</th>
<th>Constant machining parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.25</td>
<td>V= 32 m/min, and dc = 0.2 mm</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.25</td>
<td>V= 47 m/min, and dc = 0.2 mm</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>9</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.25</td>
<td>V= 69 m/min, and dc = 0.2 mm</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>13</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>0.25</td>
<td>V= 94 m/min, and dc = 0.2 mm</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>
3. MECHANICAL PROPERTIES FOR PURE COPPER SAMPLES

The mechanical properties for the pure copper (the original sample) are presented in Table 2. The image of Energy Dispersive X-ray (EDX or EDS) analysis on the SEM is shown in Figure 6 for the pure copper sample (the original sample).
Table II

<table>
<thead>
<tr>
<th>The mechanical property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength ($\sigma_y$)</td>
<td>112 MPa</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>117 GPa</td>
</tr>
<tr>
<td>Poisson’s Ratio ($\nu$)</td>
<td>0.33</td>
</tr>
<tr>
<td>Density ($\rho$)</td>
<td>8950 Kg/m$^3$</td>
</tr>
</tbody>
</table>

Fig. 6. The image of Energy Dispersive X-ray (EDX) analysis for the pure copper sample and its elemental composition.

4. RESULTS AND DISCUSSION

From the first phase, Figure 7 shows the fabricated samples for the four passes by using the ECAP die with route “C” which rotates the sample at (180°) between the individual ECAP passes [9]. Figure 8 displays the cutting by using the wire cutting machine for the four passes of the ECAP copper samples to dimensions of 20 mm in diameter and 20 mm in height.

From the second phase, Figure 9 presents the X-ray diffraction (XRD) patterns for the pure copper sample and the ECAP copper sample after four passes. Figure 9 shows the (111), (200), and (220) reflections of the copper phase. It is clear that the diffraction intensity of (111) peak for the original copper sample is strong, which indicates a clear preferred orientation. After four passes from the ECAP process, the diffraction intensity rises significantly at the peak (200), and increases slightly at the peak (220), but the (111) peak reduces slightly. Furthermore, it is shown that line broadening rises with increasing of the number of passes in the ECAP process. This broadening is associated with the variations of microstructure, it can say that the decreasing of crystallite size and lattice strain obtained by using a process of plastic deformation (ECAP process); as mentioned in the previous studies [27]–[30].

Also from the second phase, Figure 10 demonstrates the features of the microstructure of the ECAP samples by using the SEM device at low magnification (1000X). It is obvious that by increasing the number of passes the grain size of the ECAP copper sample becomes smaller than the previous pass which is in a good matching with published results in [30]–[32].
Fig. 7. The fabricated ECAP samples for the four passes

Fig. 8. The ECAP copper samples that were cut by the wire cutting machine

Fig. 9. The X-ray diffraction patterns for the pure copper sample (zero pass) and the ECAP copper sample after four passes
Fig. 10. SEM micrograph images for the microstructure of ECAP copper samples (a) the original sample, (b) after pass No. 1, (c) after pass No. 2, (d) after pass No. 3, and (e) after pass No. 4

From the third phase, the face turning processes are done on the original samples and the ECAP samples at different machining conditions; as shown in Table 1 and Figure 3. From the fourth phase, the 3D Optical Microscope (Bruker) is used to measure surface roughness for the machined samples at different machining conditions. Figure 11 to Figure 14 are presented the relation between the feed rate \(f\), mm/rev) and the arithmetic average of the absolute roughness value \(R_a\), µm) at various cutting speeds \(V\), m/min) with a constant depth of cut of 2 mm. It is shown that as the smallest surface roughness value \(R_a\) achieves at high cutting speed and low feed rate for the original samples and the ECAP sample after the first three passes. But, the ECAP samples after four passes, the ECAP copper material becomes harder. So, the lower surface roughness value \(R_a\) occurs in two cases at the low cutting speed with a higher feed rate and at the high cutting speed with low feed rate, as displayed in Figure 11 and Figure 14.
Fig. 11. The relation between the feed rate and the surface roughness value at cutting speed of 32 m/min and deep of cut of 2 mm

Fig. 12. The relation between the feed rate and the surface roughness value at cutting speed of 47 m/min and deep of cut of 2 mm
Fig. 13. The relation between the feed rate and the surface roughness value at cutting speed of 69 m/min and deep of cut of 2 mm

Fig. 14. The relation between the feed rate and the surface roughness value at cutting speed of 94 m/min and deep of cut of 2 mm

From the final phase, scanning electron microscopy (SEM) device is utilized to analyze the surface topography for the machined samples (original samples, and ECAP samples after pass-2 and pass-4) at diverse machining cutting conditions; as shown in Figure 15, Figure 16, and Figure 17. It is displayed that the surface topography is enhanced by increasing the number of passes for the ECAP copper samples and raising cutting speed with decreasing the feed rate.
Fig. 15. SEM micrograph images for the surface topography for the original machined samples

Fig. 16. SEM micrograph images for the surface topography for the ECAP machined samples after pass No. 2
5. CONCLUSION

The effects of the number of passes and machining cutting conditions on the surface roughness of commercially pure copper produced by the ECAP process were investigated. The conclusions are obtained as follows:

- At lowering values for the cutting speed (V = 32 m/min) and the feed rate (f = 0.15 mm/rev.), the ECAP machined samples after one and three passes are the best surface finish with the roughness values about of (R_a = 0.439 µm) in comparing with the roughness value of the zero pass sample (R_a = 0.632 µm) and the roughness value of the sample after four passes (R_a = 1.038 µm).

- At the low value of the cutting speed (V = 32 m/min) and high value of the feed rate (f = 0.5 mm/rev.), the ECAP machined sample after four passes is better surface finish with the roughness value of (R_a = 0.819 µm) in comparing with the roughness value of the zero pass sample (R_a = 1.631 µm) and the roughness value of the sample after three passes (R_a = 1.421 µm).

- At the high value of the cutting speed (V = 94 m/min) and low value of the feed rate (f = 0.15 mm/rev.), the zero pass machined sample is the best surface finish with the roughness values about of (R_a = 0.347 µm) in comparing with the roughness values for the ECAP samples. Because the material becomes harder by increasing the number of passes for the ECAP samples. According to previous studies, high cutting speeds are not preferred in more hard materials.

- At the high cutting speed (V = 94 m/min) and high feed rate (f = 0.5 mm/rev.), it was found that the surface roughness values for all samples were high. The largest value (R_a = 1.554 µm) was for the machined original sample (zero pass) and the smallest value (R_a = 1.327 µm) for the machined sample after four passes of the ECAP process.

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