Texture Changes during Simple Shear Extrusion (SSE) Processing of Pure Copper

E. Bagherpour, F. Qods, R. Ebrahimi and H. Miyamoto

1. Introduction

Material texture is defined as a microstructural property that describes the orientation distribution of the grains constituting a polycrystalline aggregate. Studies of texture evolution are important for understanding the anisotropy of the physical and mechanical properties of the materials processed by severe plastic deformation (SPD) methods, which involve large strain levels and frequent strain path changes. The texture of the basic and most familiar SPD techniques like equal channel angular pressing (ECAP), high pressure torsion (HPT), accumulated roll bonding (ARB) were studied widely before.

Simple shear extrusion (SSE), invented in 2009 by Pardis and Ebrahimi, is one of the most-recent SPD techniques which is based on pressing material through a specially designed direct extrusion channel. Figure 1 shows the schematic representation of the SSE channel with a linear die profile. By passing the material through SSE channel the initial square cross section (entrance plane) of the material changes to a parallelogram with a distortion angle of $\alpha$. The maximum shear strain applies at the middle of the channel (middle plane) with maximum distortion angle of $\alpha_{\text{max}}$. Through the second half of the SSE channel, the distortion angle decreases gradually and finally the materials comes back to its initial square cross section at the exit of the SSE channel (exit plane). So a shear strain of $\tan(\alpha_{\text{max}})$ is applied to the material in each half of the channel. Therefore, the total effective strain of $\frac{2 \tan \alpha_{\text{max}}}{\sqrt{3}}$ is achieved after one pass of SSE. The length of the SSE channel and subsequently the strain rate of the process depend on the maximum inclination angle ($\beta_{\text{max}}$). As it is seen in Fig. 1, each normal direction (ND) plane tilted around ND direction by the inclination angle of $\beta$. The $\beta_{\text{max}}$ is achieved at the upper and the lower ND planes. The inclination angle has a significant effect on the deformation zone, strain rate and the load of the process. Therefore, by changing the inclination angle it is possible to change the strain rate of the process without change of the total amount of strain.

The ability to apply the strain gradually to the materials made the SSE process a good candidate to impose a high amount of strain into the difficult to work materials like magnesium alloys and twinning induced plasticity (TWIP) steels at ambient temperature.

Although there are some reports on the microstructural and mechanical behavior of pure aluminum, TWIP steel and pure magnesium after SSE processing, there is not any report about the texture investigation of the samples during and after SSE process. In this work the texture of the pure copper during and after one pass of SSE has been investigated by electron back-scattering diffraction (EBSD). For this reason, samples were taken out from the die during the deformation.

2. Experimental Procedure

An SSE die with a square cross section with $\alpha_{\text{max}}$ and $\beta_{\text{max}}$ of 45° and 22.2° respectively, and a side length of 10 mm was designed and constructed. In this case the theoretical strain for each pass is 1.155. The length of the deformation channel (deformation zone) corresponds to the maximum inclination angle ($\beta_{\text{max}}$) by:

$$L = \frac{a \tan \alpha_{\text{max}}}{\tan \beta_{\text{max}}}$$

where $a$ is the side of the square cross section in the entrance.
of the channel and \( L \) is the length of the deformation channel. Using eq. (1), the length of deformation channel is 25 mm. It is possible to extract the samples during the SSE process by stopping the process and open the die as it is a two part die.

Copper billets of commercial purity with a dimension of 10 mm × 10 mm × 50 mm were machined and annealed for 2 h at 650°C and then furnace cooled to room temperature as an initial material. To reduce the friction between sample and tools, samples wrapped with Te/flon tape and silicon sprayed.

A screw press with a ram speed of 0.2 mm/Sec was used for SSE processing.

To investigate the texture of samples during the SSE process, samples were extracted from the SSE die during the deformation. As it is seen in Fig. 2, the sample was cut during the deformation after passing through the deformation channel in the distance of 0.25\( L \), 0.5\( L \) and 0.75\( L \) as well as before and after the deformation channel. Initial annealed, 0.25\( L \), 0.5\( L \), 0.75\( L \) and first pass samples were named as 0 pass, 0.25 pass, 0.5 pass, 0.75 pass and 1 pass samples respectively in this article.

For the texture investigations, electron back-scattering diffraction (EBSD) was used. After the standard metallographies procedure, the obtained surfaces were electrically polished in a solution of 30 Vol. % ethanol-70 Vol. % ml phosphoric acid with a DC voltage of 2.5 V for 15 minutes at room temperature. EBSD observations were performed by a JEOL 7001F scanning electron microscope (FE-SEM) equipped with a field emission gun operating at 20 kV. The JTEX software was used for the texture investigations.

For each sample, the area of about 1 × 1.2 mm² in the center was investigated by EBSD with the pixel size of 5.2 μm². The grain size for the 0 and 1 pass samples are about 20 and 6 μm respectively. The approximate number of the grains included in the EBSD analysis is 1110, 4980, 6650, 5250 and 6270 for 0, 0.25, 0.5, 0.75 and 1 pass samples, respectively.

### 3. Result and Discussions

The equivalent strain (\( \varepsilon_{eq} \)) in an SSE section with a distortion angle of \( \alpha \) calculated by

\[
\varepsilon_{eq} = \frac{2x \tan(\alpha_{max})}{L \sqrt{3}}
\]

where \( x \) is the distance from the entrance of the SSE channel and \( L \) is the total length of the SSE channel (see Fig. 1). The distortion angle for 0, 0.25, 0.5, 0.75 and 1 pass samples is 0°, 26.6°, 45°, 26.6° and 0° respectively; therefore using eq. (2) the corresponding theoretical strain for the 0, the 0.25, the 0.5, the 0.75 and the 1 pass samples is 0, 0.288, 0.577, 0.866 and 1.155 respectively. As it can be seen in Fig. 2 the shear strain applied gradually from the entrance to the middle of the deformation channel and the maximum shear happens in the 0.5 pass sample. After that, the shear direction is reversed and the sample is expected to become to the original square cross section at the exit. However, as it illustrated in Fig. 2, as a result of the lack of back pressure the cross section of 1 pass sample is not completely square. This is the reason of the change in the length of the sample from 50 mm to 53.1 mm after a pass of SSE which means an elongation in the length of 6.2%.

As it is illustrated in Fig. 1, during the deformation channel, a sample extruded in the SSE die is distorted on the ED-plane in TD-direction (namely, shear happens in ND-plane)\(^9\). Therefore, it is legitimate to think that SSE textures would be similar to that of simple shear textures. The most important ideal orientations in simple shear are distributed along the two fibers with a crystallographic slip direction parallel to the shear direction and a crystallographic slip plane parallel to the shear plane, respectively\(^15-17\). These fibers are \([hkl]/(110)\) fiber (or \((110)-fiber in short) and the\([111]/(uvw) fiber (or \{111\}-fiber in short) for FCC materials. The Miller indices and Euler angles of the main ideal orientation of the simple
shear fibers are given in Table 1. In this study, the textures are represented in the TD-ND-ED reference system and the orientations are specified in terms of the \( (hkl) \) plane parallel to the ND-plane and the \( (uvw) \) direction parallel to the TD-direction (See Fig. 1). The evolution of component of simple shear texture in the first section of the orientation distribution function (ODF) during one pass of SSE is shown in Fig. 3. In the initial stage of deformation (Fig. 3(b)), the \( A_1^* \) and \( A_2^* \) components appeared from a fully annealed texture (Fig. 3(a)). In the 0.5 pass sample, all three ideal components appearing in this section are well developed (see Fig. 3(c)). The \( A_1^* \) and \( A_2^* \) components show some fiber nature in both 0.25 and 0.5 pass samples. In the second half of deformation channel, by reversing the shear direction the \( C \) component eliminates and the major components are \( A_1^* \) and \( A_2^* \). However, the intensity of \( A_1^* \) and \( A_2^* \) components of 0.75 pass sample (Fig. 3(d)) is lower than the 0.5 pass sample (Fig. 3(c)). The crystallographic orientation in the second half of the channel

<table>
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<th>Notation</th>
<th>( (hkl) ) ( (uvw) )</th>
<th>Euler angles (°)</th>
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<tr>
<td>( A_1^* )</td>
<td>(111)[112]</td>
<td>35.26/215.26 45 0/90</td>
</tr>
<tr>
<td></td>
<td>125.26</td>
<td>90 45</td>
</tr>
<tr>
<td>( A_2^* )</td>
<td>(111)[112]</td>
<td>144.74 45 0/90</td>
</tr>
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<td></td>
<td>54.74/234.74</td>
<td>90 45</td>
</tr>
<tr>
<td>( A )</td>
<td>(111)[110]</td>
<td>0 35.26 45</td>
</tr>
<tr>
<td>( A )</td>
<td>(111)[110]</td>
<td>180</td>
</tr>
<tr>
<td>( B )</td>
<td>(112)[110]</td>
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<td>60/180</td>
</tr>
<tr>
<td>( C )</td>
<td>(001)[110]</td>
<td>90/270</td>
</tr>
<tr>
<td></td>
<td>0/180</td>
<td>90 45</td>
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Fig. 3 The \( \varphi_2 = 0^\circ \) section of the ODF of (a) the 0 pass, (b) the 0.25 pass, (c) the 0.5 pass, (d) the 0.75 pass and (e) the 1 pass, pure copper samples during SSE.
would resemble the initial texture as a result of the reversing the shear through the second half of the SSE channel. As shown in Fig. 3(c) after the exit of the channel (1 pass sample) still the $A_1^*$ and $A_2^*$ components are the major components, their intensity, however, is higher in the 1 pass compared to 0.75 pass. Compare Fig. 3(e) with Fig. 3(b) it is known that the texture of the 1 pass sample is more similar to the 0.25 pass sample. Therefore, although resemblance of the textures to the simple shear textures reduces by distancing from the middle plane but the simple shear textures are still the major components after the exit of the channel which means that the initial textures are not recovered completely. The same trend was reported for the ECAP processing by route C$^{19}$ which is considered the reversal route.

Figure 4 displays the $\phi_2 = 45^\circ$ section of the ODF. For all the samples the main components are $A$, $A_1^*$ and $B$ components. For the 0.5 pass sample the $C$ component still has the highest intensity. The 0.5 pass sample has the highest intensity of the components (Fig. 4(c)). Same as the first section of ODF, after a pass of SSE, some components of simple shear remains with lower intensity (see Fig. 4(e)). In this section the highest intensity component is $A_2^*$ after a pass of SSE. For both, $\phi_2 = 0^\circ$ and $\phi_2 = 45^\circ$, the simple shear textures are not so strong even for the 0.5 pass sample; the result comes from the fact that the amount of shear in the middle plane (0.5 pass) is 1 which is not so high$^{20}$.

For all the samples, the $B$ and $A_2^*$ components rotate by about $10^\circ$ in the sense of rigid body rotation with respect to the ideal orientation. The $A$ and $A_1^*$ components rotate same as $A_2^*$ but in a reverse sense. The rotation in the sense opposite to rigid body motion is the characteristics of simple shear while the rotation in the sense of the rigid body motion is the characteristics of the ECAP process$^{20}$. The rigid body rotation is inherent in simple shear and it affect the texture of the materials based on the materials slip systems and consequently its strain rate sensitivity$^{17,21}$.
Figure 5 shows the volume fraction of each simple shear components of textures for all the samples. As it is seen the 0.25 and the 0.5 pass samples has the strongest textures and after the reversing the shear strain the simple shear textures reduce gradually. All the components of shear strain are developed well for the 0.25 and the 0.5 pass samples while for the 1 pass sample only some of the components are seen. The major texture component for 0.25, 0.5, 0.75 and 1 pass samples are A∗2, C, A∗1 and A∗2 respectively. The distribution of texture after a pass of SSE is similar to 0.25 pass sample but with lower intensity. Also, it is interesting and unexpected that the intensity of simple shear texture is higher in the 1 pass sample than the 0.75 pass sample but as it is expectable its lower than 0.5 pass sample.

The φ2 = 0° and φ2 = 45° sections of ODF on ND and TD planes of the 1 pass sample are shown in Fig. 6. Comparing the ODF sections of the ED-plane with the ND and the TD planes it can be concluded that the textures on ND plane is closer to the ideal orientation of simple shear as it was expected. The major texture components for ND-plane are A, A∗2, A and A∗1 (see Fig. 6(a) and (b)). As it is seen in Fig. 6(c) and (d) the A and A components are the strongest shear components on TD-plane. Therefore, the orientation of TD plane is more similar to initial texture and the simple shear textures are not developed well for this plane. For the ND and the TD planes the major component is the A component while it is the A∗2 for the ED-plane.

4. Conclusion

In the present work the texture evolution of pure copper during and after the first pass of simple shear extrusion technique was investigated by EBSD observations. For this reason, samples were taken out from the SSE die during the process. From the beginning to the middle of the deformation channel, the simple shear textures were formed gradually and the strongest simple shear textures were observed on the 0.5 pass sample. As a result of the shear reversal, the degree of the simple shear textures decreases gradually with the distance from the middle plane but the simple shear textures were still the major components after the exit of the channel; this means that the initial textures were not recovered completely. After a single pass of SSE, the most and the least similarity to the simple shear textures were seen in the ED and the TD planes, respectively. The major orientation components after first pass were the A∗2, A and A on ED, ND and TD planes, respectively. However, the major component for the 0.5 pass sample was the C component.

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REFERENCES