Investigation of microstructure and mechanical properties of copper shell produced by shear spinning in different rotation directions

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Abstract

In this study, the effect of alteration in the direction of forming during the shear spinning of C11000 copper metal on mechanical properties, microstructure, texture, and anisotropy was investigated. Shear spinning causes the grains stretching along the axial direction besides increasing the grain length in the circumferential direction. Strain–path change in the shear spinning specimens has somewhat resulted in finer grains, more grain refinement, and a higher percentage of high-angle boundaries. More change of strain direction in the shear spinning specimens resulted in approximately 9% to 11% reduction in strength, from 1% to 9% decrease in hardness, and increased elongation from 7% to 37% more than in the specimen without path change. Shear spinning specimens in different paths had different orientations and texture intensities. In the specimen without strain–path change, most of the texture is related to \{123\} \{412\} orientation and copper texture with \{112\} \{111\} orientation. In the shear spinning specimens in other paths, textures with \{001\} \{100\}, \{011\} \{011\}, and \{211\} \{011\} orientations and brass texture with \{110\} \{112\} orientation were strengthened. Due to the change in texture and mechanical properties, the strain-path change in the shear spinning process reduced the anisotropy in the C11000 copper metal.

1. Introduction

Copper and its alloys are among the non-ferrous metals that have a special place in various industries because of characteristics like strength, formability, and creep, corrosion and fatigue resistance as well as excellent electrical and thermal conductivity [1]. Grain refining is an efficient technique that is utilized to strengthen metals while maintaining their chemical composition. One standard method for grain refining is cold deformation [2]. Shear spinning is also one of the forming methods for grain refining. It is one of the ways of forming metals that can produce hollow volumes and seamless with the axis of symmetry such as cones, cylinders, pipes, hemispheres, or a combination of them. This process is widely used to produce parts needed in the oil and gas industries, automotive, pressure vessels, kitchen appliances, etc. For proper use of these devices, the final properties of the manufactured part are essential [3]. Using the shear spinning method, symmetrical thin-wall parts can be produced with high accuracy and strength, great quality of the surface, and uniform thickness of walls. Because in the process of shear spinning the force is locally applied to the work-piece by the tool, the deformation pressures are significantly lower than conventional compression forming. The result is that under lower deformation forces, much greater pressure can be applied to the work-piece. Thus, in many circumstances, there is merely one pass that is required for final part production. Moreover, a significant reduction in thickness is achieved without annealing between the deformation steps [4]. Figure 1 depicts the process of shear spinning and the equipment as well as the machine components.

Unlike the traditional spinning method, in which the thickness does not change, in the shear spinning method, the thickness of the work-piece changes dramatically during the process, which can only be done
through power spinning with special equipment [5]. The reason for this naming is the pure shear force that is applied to the work-piece and reduces the thickness, thus thinning its wall [6]. In the shear spinning process, the roller reduces the wall thickness of the work-piece in a predictable and calculated way. At the same time, the blank diameter always remains constant during the process. The final thickness of the work-piece in conical shear spinning, produced from flat raw parts, follows equation (1), known as the Sine law [6–8], as shown in figure 2.

\[
t_f = t_0 \sin \left( \frac{\alpha}{2} \right) \\
\]

\[
r = 1 - \sin \left( \frac{\alpha}{2} \right) \\
\]

Where \( t_f \) is the final thickness of the work-piece, \( t_0 \) is related to the preform primary thickness, and \( (\alpha/2) \) is half the mandrel conical angle. Obviously, the result is usually slightly different from what is obtained from the sine law in real life [6]. In most researches [4, 9–11] that have been done on shear spinning and microstructure of different materials and metals, it has been observed that during shear spinning, grain refinement is gradual not only in the small grains but also in the large ones as the thinning is escalated. These grains are stretched along axial as well as circumferential directions. Also, hardness and strength gradually increase as the wall thickness decreases.

Various studies on the development of texture and microstructure due to different process factors in forming other materials have been reviewed. However, one of the less considered parameters is the influence of alterations in strain-path in the course of construction. Traditionally, the effects of strain-path have been investigated by a reversal of uniaxial deformation like the Bauschinger effect and also by an amalgamation of shear and uniaxial deformation. The main focus of strain-path change is the production of sheets with different textures and microstructures that show other properties. For example, in the rolling process, alteration in the strain-path can be attained by alternating the rolling direction (RD) [12]. Strain-path change has a remarkable effect on the enhancement of metals texture and microstructure, particularly the FCC metals like nickel and...
copper. Strain-path change due to weaker texture can lead to more consistent characteristics. Consequently, strain-path change can be regarded as an exclusive method for enhancing the materials properties [13]. The change of strain-path can influence the properties of materials through various ways, including alterations in the texture of crystals as well as microstructural changes together with fluctuations of the distribution of residual stress and variations of plastic anisotropy [14]. Simultaneously, changes in the properties of the plastic, such as softening of the deformation, are observed, which can be one of the advantages of this method. One of the issues that should be considered in relation to the strain-path change is the adjustment of texture. In this manner, formation of desirable texture compounds and also removal of undesirable texture can be controlled [15].

In a research conducted by Suwas et al [16] on the specimens of pure copper metal that were subjected to a strain-path change in the rolling process, it was found that in a specimen rolled uni-directionally, a strong texture of the Cu type was formed by combining peaks of Cu and S. In contrast, in the specimen with the change in the rolling direction, a weaker texture of the same kind was observed.

Cold work on metal causes the microstructure to orient along with the deformation, resulting in mechanical properties and ultimately anisotropy. Plastic anisotropy, denoted by R, is one of the parameters used to determine the amount of anisotropy of the material in different directions [7].

\[
R = \frac{\varepsilon_w}{\varepsilon_t}
\]

(3)

where R is the plastic anisotropy, \((\varepsilon_w, \varepsilon_t)\) is the true strain in the direction of the width, and \((\varepsilon_t)\) is the true strain in the direction of thickness in a uniaxial tensile test. If \(R = 1\), the sheet behaves similarly in both transverse and thickness directions. But normally, the R value is not one, which indicates the dissimilarity in the sheet behavior in the stated directions and is expressed by the term anisotropy. \(R_m\), which is also named as vertical anisotropy, is the average value of anisotropy in different directions, and can be defined as follows:

\[
R_m = \frac{R_0 + 2R_{45^\circ} + R_{90}}{4}
\]

(4)

Planar anisotropy is another indicator and one of its applications is to express the extent of the edges earing on the walls of deep drawn cups. The planar anisotropy value is obtained from the following equation. For an utterly isotropic sheet, it is assumed that \(\Delta R = 0\) and \(R_m = 1\) [7].

\[
\Delta R = \frac{R_0 - 2R_{45^\circ} + R_{90}}{2}
\]

(5)

The change of the forming direction will fluctuate the material properties. But research on the change of the forming direction in the shear spinning process has received less attention. Changing the direction of rotation of the mandrel and changing the mold angle will result in alterations of texture, mechanical properties, and microstructure of the shear spinning parts. In this research, texture, anisotropy, microstructural changes, and mechanical properties of the shear spinning specimens in different paths of the C11000 copper alloy with the same thickness reduction are investigated and compared, and the results are discussed.

2. Materials and methods

In this study, electrolytic tough-pitch copper (ETP) was used under the brand name C11000. Table 1 presents the chemical composition analysis of the C11000 alloy.

All specimens were subjected to a full annealing process in order to decrease the influences of hardness and the rolling process and sheet production, to homogenize the microstructure, and to control the cold working process at 600 °C for 1 h to a greater extent. Shear spinning was performed using a mandrel with angles of 120°, 90°, and 60° in 4 paths. The shear spinning paths are shown in table 2 and schematically in figure 3. According to equation (2), the thickness reduction in shear spinning using a mold with an angle of 120° is equal to 13.4%, with a mold of 90° is equal to 30%, and with an angle of a mold of 60° is equal to 50%. The shearing spinning machine is of Lifield Spinner type which uses two rollers. Circular sheets (primary thickness = 5 mm, final thickness = 2.5 mm, diameter = 150 mm) were selected. The process specifications are as follows: the spindle speed = 500 rpm, the roller tip radius = 12 mm, the roller diameter = 160 mm, and the advance speed = 150 mm min\(^{-1}\). Figure 4 shows the shear spinning machine and specimens with different mold angles.

Metallography was performed on the shear spinning specimens. The specimens were cut and mounted from the shear spinning parts on the T-N and R-N planes (the metallographic specimens location can be seen in figure 5).

The specimens surfaces were polished using 220 to 3000 sandpapers. The specimens were then etched in 150cc HCl +10 g FeCl\(_3\) + 100cc H\(_2\)O solution, and were then examined using optical microscopy (OM). The grain size was investigated by ASTM E112 standard. Electron backscatter diffraction (EBSD, OXFORD machine) was utilized to investigate the grains distribution and also grain boundaries of the shear spinning specimens. The
specimens were prepared for EBSD analysis after mechanical polishing by electro-polishing using a solution of 50cc H₃PO₄ + 50cc C₂H₅OH + 100cc H₂O.

Uniaxial tensile test was used to investigate the changes in strength and relative elongation of the sheet under the forming process. The specimens for tensile test were prepared as per the ASTM E8M standard from the shear spinning parts to examine the differences between mechanical as well as anisotropy properties in the 0°, 45°, and 90° directions compared with the forming direction. Figure 6 shows how the tensile test specimens are positioned in the 0°, 45° and 90° directions, taking into account the forming direction. Anisotropy and microhardness was also assessed using the ASTM E517 and ASTM E384 standard respectively.

![Figure 3. Schematic of different shear spinning paths with mold angles and rotation directions.](image)

Table 1. Chemical analysis of C11000.

|     | Cu  | O   | P   | S   | Al  | Pb  | Ni  | Zn  | Sb  | Sn  | Si  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| %   | 99.9869 | 0.013 | 0.0039 | 0.0008 | 0.0015 | 0.0012 | 0.0011 | 0.0009 | 0.0001 | 0.0002 |

Table 2. Instructions for performing different shear spinning paths, based on the mold angle and rotation direction.

| Sample name | Number of passes | Mold angle/Direction of rotation |
|-------------|------------------|---------------------------------|
| A           | 1                | 120° Clock-wise                  |
| B           | 2                | 90° Clock-wise                   |
| C           | 3                | 90° Counter-clockwise            |
| D           | 3                | 60° Clock-wise                   |

specimens were prepared for EBSD analysis after mechanical polishing by electro-polishing using a solution of 50cc H₃PO₄ + 50cc C₂H₅OH + 100cc H₂O.
Figure 4. (a) Shear spinning machine, (b) Shear spinning specimens with different mold angles.

Figure 5. Position and location of the metallographic specimens on the R-N and T-N planes in the shear spinning process.

Figure 6. Preparation of the tensile test specimens for shear spinning in three directions of 0°, 45°, and 90°.
3. Results and discussion

3.1. Microstructural studies

Microstructural images of the initial annealed and the shear spinning parts in different paths on the planes of R-N and T-N are shown in figures 7–11. By observing the microstructural images of these planes in the shear
spinning patterns of different paths, it can be seen that the shear spinning process in copper has caused grain refinement in all the tested paths. The grains are stretched along the spinning axis and extended in a circumferential direction. The grain elongation on plane R-N is greater than on plane T-N in all specimens. Similar results have been reported by Radović et al. [4], Wang et al. [10], Gur et al. [17], and Zhan et al. [9] as well. The grain length and width sizes on these two planes are shown in figure 12. According to the diagram of figure 12, the largest grain size is related to specimen A. Also, specimen C has the smallest grain size. It can be inferred that the greatest amount of grain refinement is ascribed to specimen C and the smallest amount of grain refinement is related to specimen A. This elongation of the grains in the microstructure has caused deformation bands. We can observe the shear bands in the microstructure as well. These bands in the shear spinning specimens appear because of the nature of the shear forces introduced in the shear spinning process.

As we know, the main mechanism in plastic deformation is dislocation slip. Depending on the applied strain and the primary orientation it results in forming micro-bands, dislocation walls, and dislocation cells. The existence of deformation bands has been reported by Liu and Hansen [18]. Based on their study, the grains could be divided into four macroscopic or deformation bands (DB) which were parallel to the rolling plane. Between these bands, three transition bands exist and the direction is constantly changing from DB to the adjacent band. Also, in strains ranging from medium to large, the shear bands appear as a particular indicator of local plastic instability [19]. The primary mechanism of deformation during the shear spinning process is pure shear stress [20]. In the deformation zone, the rollers compressive stress causes axial shear stress, and upon rotating of the part with the mandrel, torsional torque is transferred, resulting in rotational shear stress [9]. Due to the presence of primary coarse grains and heterogeneous stresses, the grains are divided into different areas under different strains, resulting in different grain orientations. By creating deformation in the material, misorientation between the areas increases, leading to the formation of high angle boundaries and hence deformation bands. In the deformation bands, due to shear deformation, parallel geometrically necessary boundaries (GNB) are developed at the angle range of 20°–40° to the direction of rolling. As deformation increases, the GNBs misorientation is escalated due to the non-uniform strain of the DBs interior. This may cause the secondary and even third DBs formation and further refinement [9]. Because different grain areas might undergo different strain amounts and since misorientation between the two bands escalates with the increase in deformation, grain refinement in the C11000 alloy can be based on the grain fragmentation into deformation bands, which causes
The macroscopic decomposition of the grains, as shown in EBSD of the shear spinning specimens in different paths in figure 13.

Figure 14 shows the high (black color) and low angle (red color) boundaries in the shear spinning specimens microstructure in different paths. Misorientations of $2^\circ < \theta < 15^\circ$ have been assigned for defining low angle boundaries, while $15^\circ < \theta$ misorientations are used for defining high angle boundaries.

The high to low angle boundaries (HGAB/LGAB) ratio in the shear spinning specimens for specimens A, B, C and D is $(0.34/0.66), (0.35/0.65), (0.37/0.63),$ and $(0.35/0.65),$ respectively. Considering the frequency ratio of high to low angle boundaries, it can be seen that this ratio is very close in all specimens and is the highest value in specimen C. This could be due to the shear stresses in the opposite directions and successive passes on the T-N plane. According to the EBSD images, during shear spinning the grain boundaries are formed along GNBs for the fragmentation of the grains. In the shear spinning process, a great number of small sub-grains are constructed. Several twins have also been observed in the deformed structure, although the number of twins is small. Twins during deformation not only create independent slip systems but also cut large grains and turn them into fine grains. This was also observed by Wang et al [21]. Cross-slip of dislocations and twins in materials with low stacking fault energy (SFE) such as copper is one of the most significant mechanisms of deformation.
During deformation processes, grain refinement involves different mechanisms. One of the major reasons for grain refinement during cold work or warm work is continuous dynamic recrystallization \[23, 24\]. The grains become fragmented by creating low angular dislocation boundaries due to deformation and, subsequently, a gradual escalation in the grains misorientation occurs, which eventually leads to the conversion of the grains to the normal boundaries \[25\]. According to Zhao et al \[26\], grain refinement can be achieved through formation of micro-bands, formation of thin lattice structures in these microbands, and formation of stretched grains in local shear bands. Xia et al \[27\] also stated that the reason for the evolution of microstructure during shear spinning could be grain division. As a result, high plastic deformation of grain dislocations gradually increases until cellular structures are formed. These cellular structures become sub-grains when subjected to plastic deformation. These sub-grains form independent grains as the angle of misorientation increases, and their boundaries become high angle boundaries. Also, the intersection of deformation bands (DBs) can lead to the division of the grains into multiple sub-grains.

According to the pole figures in figure 15, the shear spinning specimens in different directions have different texture orientations and intensities. In specimen A, most of the texture is related to \{123\} \{412\} orientation and the copper texture is related to \{112\} \{111\} orientation. In specimen B, the most texture was related to \{441\} \{111\} orientation, copper texture was \{112\} \{111\} and texture \{111\} \{110\}, and in specimen C, most of the texture was related to cubic texture with orientation \{001\} \{100\} and orientations \{011\} \{011\} and \{112\} \{211\}, and in specimen D, most of the texture was related to brass texture with orientation \{110\} < \{112\} and textures \{211\} \{011\} and \{110\} \{111\}. In specimens B, C, and D, which have experienced the strain direction change during shear spinning, the orientations have more shear texture components. This difference in texture and intensity can be related to the difference in the formation paths and strain heterogeneity. Yan et al \[28\] considered that for the FCC materials with low stacking fault energy (SFE), the shear banding was the chief mechanism responsible for texture transfer from copper to brass at large deformations. This indicates that the shear bands have also been developed by changing the strain-path. Yang et al \[29\] also stated that by changing the direction of rotation in the power spinning process, more sliding systems may be activated in the specimens which experienced the change in the strain direction. As a result, a more homogeneous texture is formed in these specimens. Suwas et al \[30\] showed that in the copper rolling process, the components of copper texture, brass and S \{123\} \{634\} are present and the copper and S components are weakened by changing the strain direction. On the other hand, the brass texture components or those components that are close to it, \{011\} \{111\} or \{011\} \{211\}

![Figure 15. Pole figure images of the shear spinning specimens (a) A, (b) B, (c) C, and (d) D.](image-url)
(311), are present in the copper metal texture with a change in the strain-path. The shear bands in microstructural images of the rolled copper samples were also noticed. Upon two or more steps of changing the forming direction, the shear bands direction relative to the unidirectional rolling specimen changed, and in both directions the shear bands could be found. Wang et al. [10] claimed that the shear strain was the cause of grain refinement. Apart from that, a change in the load direction causes the GNBs intersection and creation of high angle grain boundaries.

3.2. The tensile test
Tensile test was conducted on the initial annealed specimen and shear spinning parts in 4 different paths in three directions of 0°, 45°, and 90°. The results of the tensile test are presented in figure 16. As can be observed in this figure, shear spinning of the C11000 copper metal has augmented the strength and reduced elongation in all three directions of 0°, 45°, and 90°. This is due to the increased work hardening, increased density of dislocations, and reduced grain size.

Figure 17 shows the comparative graph of tensile strength, and figure 18 shows a comparative diagram of the percentage of elongation in three directions of 0°, 45°, and 90° relative to the forming axis in the initial annealed and the shear spinning specimens in different directions. According to figure 17, it can be perceived that the reduction in grain size due to the spinning process has increased the strength according to the Hall-Petch relationship. The Hall-Petch relationship for bulk metals is:

\[
\sigma_y = \sigma_0 + Kd^{-\frac{1}{2}}
\]

where \(\sigma_y\) is the yield stress, \(\sigma_0\) is a lattice friction stress, and K is a constant of yielding, d is the average grain size [31]. The maximum strength is related to specimen A and the lowest strength is related to specimen C. Also, the strength in the direction of the main shear spinning axis in all specimens is the highest and in the direction of 90° relative to the forming axis it is the lowest. This indicates that most of the grain refinement is done in the direction of the shear spinning axis. Figure 18 shows the shear spinning process in copper has caused decrease the elongation in all the tested paths. The highest value of elongation is attributed to specimen C and the lowest value is related to specimen A. Also, due to the two changes in the direction of the forming of specimen C, it had less strength and a higher elongation compared with specimens B and D, which experienced one change in the direction of forming. According to a study by Ostafin et al [15], the strain-path change of plastic deformation in the copper sheets destabilizes the sub-structure and results in substantial microstructural changes along with alterations in the distribution of grain orientation (crystalline texture). These alterations lead to variations of mechanical and plastic properties and suppression of deformation twinning. Based on their obtained results, the strain-path change in the copper sheets will lead to the formation of appropriate textures and decrease detrimental textures. The strain-path change in specimens B, C, and D reduced the grain size. We expect that according to Hall-Petch relation the finer grain size should induce an escalation of strength. At the same time, a
strain-path change in shear spinning is followed by the reduction of strength and enhancement of elongation in relation to unidirectional shear spinning. This could be due to the creation of a weaker crystalline texture as well as dynamic recrystallization as a consequence of the strain-path alteration. This has also been observed in Zhang et al\cite{32} and Rout et al\cite{14}.

The $\Delta R$ and $R_m$ anisotropy values in the shear spinning specimens were calculated in line with the obtained strain in the transverse and longitudinal directions of the samples of tensile test, as shown by the diagram in figure 19.

According to the values obtained from $\Delta R$ and $R_m$ related to the initial annealed and the shear spinning specimens and also the diagrams of figure 19, we can see that anisotropy increased by shear spinning and the $\Delta R$ and $R_m$ values decrease as the strain direction changes. Thus, alteration in the deformation direction during shear spinning results in the reduction of anisotropy. Similar to the results of Goli et al\cite{33} study, the strain orientation change has been an efficient technique for decreasing the anisotropy of mechanical properties of the C11000 alloy. These results comply with those reported by other researchers such as Rout et al\cite{14}, Wronski et al\cite{34}, etc. So, the strain-path change in the C11000 alloy can result in the formation of a shell with relatively more isotropic properties in different directions in comparison with unidirectional shear spinning.

3.3. Micro-hardness evaluation

Micro-hardness assessment was done on the shear spinning parts in different paths on the three planes of R-T, R-N, and T-N figure 20 represents the microhardness test results in the form of a diagram. Considering that micro-hardness of the initial annealed specimen is equal to 50 Vickers, it is revealed that by performing the shear spinning process in different paths in all three planes, the hardness value has increased drastically. This increase in hardness is the increase in dislocations density, more refined grains, and shorter grain boundary distance. Also, specimen A, which has no change in the direction of rotation of shear spinning, has the highest amount of
micro-hardness. The lowest amount of micro-hardness is related to specimen C with two changes of direction of rotation. By changing the direction of rotation in specimens B, C, and D, micro-hardness is reduced. This reduction in micro-hardness is due to more grain refinement, more active slip planes, and less dislocations density.

4. Conclusion

In this research, specimens of C11000 copper were subjected to the shear spinning process in different directions. The following results were obtained:

1. Shear spinning has caused the grains elongation in the axial direction and increased the grain length in the circumferential direction. However, in the axial direction this elongation of the grains is greater compared with the circumferential direction. Alteration of strain-path in the shear spinning specimens has somewhat resulted in more grain refinement and a higher percentage of high-angle boundaries. This is the change in the shear strains direction and subsequent existence of the shear bands in the opposite directions and, as a result, the division of the grains.

2. Mechanical properties of the shear spinning specimens in different paths improved compared to the original annealed specimen. Strength and hardness increased, and the elongation decreased. In the shear spinning specimens in different paths, in the case of specimen C, which had more strain-path change, strength was reduced by 9% to 11%, hardness by 1 to 9% less, and elongation by 7% to 37% higher than the specimen without path change.

3. The shear spinning specimens in different paths have different orientations and texture intensities. In the specimen without strain-path change (specimen A), most of the texture is related to the \{123\}〈412〉 orientation, and the copper texture is related to the \{112\}〈111〉 orientation. On the other hand, in the shear spinning
specimens in other paths, textures with \{001\} \{100\}, \{011\} \{011\}, \{211\} \{011\} orientations and brass texture with \{110\} \{112\} orientation are strengthened.

4. The shear spinning on copper samples increased anisotropy compared to the initial annealed sample. Due to the change in texture and mechanical properties, the strain-path change in the shear spinning process has reduced the anisotropy in the C11000 alloy relative to unidirectional shear spinning sample.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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