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Investigation and Comparison of Microstructure and Mechanical Properties Between Parts of Shear Spinning and Rolled

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Abstract

In this study, the shear spinning process and the rolling process on C11000 copper metal with a thickness reduction of 50% at room temperature were performed and investigated. In the shear spinning specimen, the grains are stretched in the axis direction and elongated in the circumferential direction. In the rolled specimen, the grains are extended in the direction of rolling, and the elongation of the grains in the T-N plane is less than in the shear spinning specimen. EBSD analysis showed that the ratio of high angle boundaries to low angle boundaries in the shear spinning specimen is higher than the rolled specimen. The mechanical properties of the rolled and shear spinning specimens were investigated in three directions of zero, 45, and 90 degrees relative to the forming direction, which showed that the strength in all three directions was higher in the rolled specimen than in the shear spinning specimen. The elongation in the shear spinning specimen is more than in the rolled specimen. The highest amount of tensile strength in the rolled specimen is about 370 MPa, and the highest elongation is about 12% in the shear spinning specimen. Also, anisotropy in shear spinning specimens was less than rolled specimens.

Keywords: Spinning, Shear Spinning, Rolling, Mechanical Properties, Copper.

1. Introduction

Copper is a non-ferrous metal that combines excellent electrical and thermal conductivity, strength, formability, and resistance of creep, corrosion, and fatigue and is widely used in various industries [1]. Grain refining is one of the effective methods for strengthening metal materials without changing the chemical composition and one of the standard techniques of grain refining is cold deformation [2]. Cold rolling and spinning are forming methods that cause grain refining. Spinning is a method of forming metals that has the ability to produce seamless and hollow volumes with an axis of symmetry such as cones, cylinders, tubes, hemispheres, or a combination of them. This process is widely used to produce parts needed in the oil and gas industry, automotive, pressure vessels, kitchen appliances, etc [3]. Shear spinning is the most effective technology for the production of symmetrical thin-walled parts with high accuracy, high strength, high surface quality, and uniformity of wall thickness with a combination of optimal properties. Because the tool applies force locally to the workpiece during spinning, the deformation pressures are significantly lower compared to conventional compression forming processes such as rolling. The result is that with fewer deformation forces, much more pressure can be applied to the workpiece. Therefore, in this process, only one pass is required to produce the final workpiece, and the large reduction of the thickness achieved without annealing treatment between stages of deformation [4]. Fig. 1. represents a schematic of the spinning machine and its equipment.

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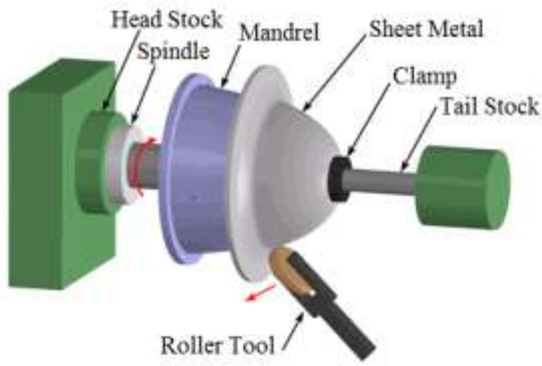

Fig. 1. Schematic of the spinning process [3].

In the shear spinning, the thickness of the workpiece is significantly reduced, which can be done through power spinning with special equipment [5]. In this method, the roller in each pass reduces the workpiece wall-thickness in a predictable and calculable way, while the blank diameter remains constant during the process. The final thickness of the workpiece in conical shear spinning follows Eq. (1)., which is called the sine law, as shown in Fig. (2). [6, 7]:

$$t_f = t_0 \sin\left(\frac{\alpha}{2}\right) \qquad \text{Eq. (1).}$$

$$r = 1 - \sin\left(\frac{\alpha}{2}\right) \qquad \text{Eq. (2).}$$

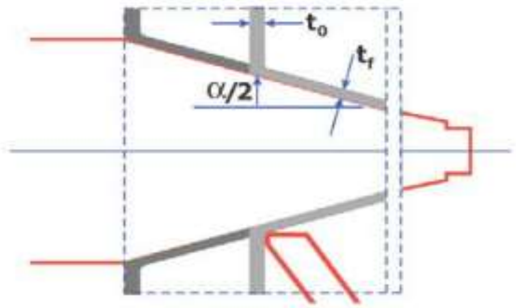

Fig. 2. Sine law [8].

Where t_f is the final thickness of the workpiece, t_0 is the initial thickness of the preform, and (α / 2) is the half-angle of the mandrel cone. However, the result is in real condition usually slightly different from what is obtained from the sine law [6, 8].

Since reducing grain size leads to increased strength and reduced ductility, it is necessary to determine the optimal grain size to create an acceptable balance between these properties. Grain size control can be achieved by controlling the parameters of thermomechanical operations (thickness reduction, strain rate, temperature) and material properties (chemical composition, phases and particles present, recrystallization and recovery mechanisms, etc.). In most studies on shear spinning and microstructure of various materials and metals, it has been observed that during shear spinning, grain refinement occurs gradually in both small and large grains with increasing thickness decrease. The grains are stretched in an axial direction and are elongated in the circumferential direction. The final tensile strength and hardness gradually increase with increasing wall thickness [4, 9, 10, 11]. Anisotropy is the orientation of mechanical properties as a result of cold work and is obtained by Eq. (3) [7]:

$$R = \frac{\varepsilon_w}{\varepsilon_t} \quad \text{Eq. (3).}$$

Where R is the plastic anisotropy, (ε_w) the true strain in the width direction, and (ε_t) the true strain in the thickness direction in a uniaxial tensile test. If R = 1, the sheet behaves similarly in both transverse and thickness directions. But generally, the value of R is not equal to one, which indicates the difference in the behavior of the sheet in these two directions and is expressed by the term anisotropy. R_m is the average value of anisotropy in different directions, also called vertical anisotropy, which is defined as follows.

$$R_m = \frac{R_0 + 2R_{45^\circ} + R_{90}}{4} \quad \text{Eq. (4).}$$

Plane anisotropy is another indicator that one of its applications is to express the degree of earing of the edges on the sides of deep drawing cups. The plane anisotropy value is obtained from Eq. (5). For an utterly isotropic sheet, it is ΔR=0 and R_m=1 [7]:

$$\Delta R = \frac{R_0 - 2R_{45^\circ} + R_{90}}{2} \quad \text{Eq. (5).}$$

Many researchers have studied the mechanical aspects of rolling and shear spinning processes, and both techniques have been discussed more or less separately from a metallurgical point of view.

In this study, due to the similarity of the two methods of sheet rolling and shear spinning, microstructure, mechanical properties, and anisotropy of rolled and shear spinning specimens made of C11000 copper alloy with the same thickness reduction have been studied and compared together. The results obtained from it are evaluated.

2. Materials and Methods

In this study, electrolytic tough-pitch copper (ETP) was used under the brand name C11000. The chemical analysis of this alloy obtained from atomic absorption spectroscopy (AAS) analysis is shown in Table. 1.

All specimens were subjected to a full annealing process to reduce the effect of hardness, eliminate the effects of rolling process and sheet production, homogenize the microstructure, and better control the cold working process at 600 ℃ for 1 hour. Cold rolling was performed by a two-roller rolling machine with a roller diameter of 55 mm.

A rolling speed of 10 m/min is selected. Fig. 3. shows the device and the rolled specimens. The initial thickness of the sheet is 5 mm, and the final thickness of the rolled sheets is 2.5 mm, and a total thickness reduction of 50% has been given.

Table. 1. Chemical analysis (wt.%) of C11000 alloy

Cu	O	P	S	Al	Pb	Ni	Zn	Sb	Sn	Si
99.9869	0.0130	0.0039	0.0008	0.0004	0.0015	0.0012	0.0011	0.0009	0.0001	0.0002

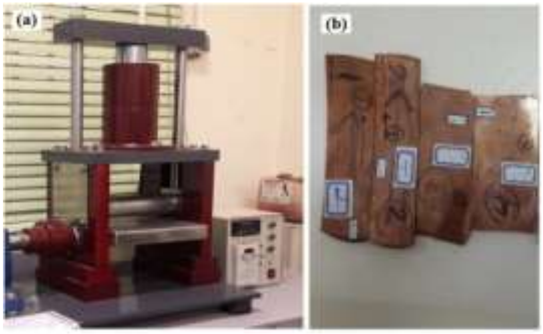

Fig. 3. (a) The rolling machine used and (b) the rolled specimens.

Shear spinning was performed using a mandrel with an angle of 60°. The thickness reduction in shear spinning with a mold angle of 60° is equal to 50%. The shear spinning process of the specimens was performed using the Lifeild Spinner, which uses two rollers. The prototype was circular sheets with an initial thickness of 5 mm and a diameter of 150 mm. The final thickness of the shear spinning specimen is 2.5 mm. The process specifications are as follows: spindle speed 500 rpm, roller tip radius 12 mm, roller diameter 160 mm, and progress speed 150 mm/min. Fig. 4. shows the shear spinning machine and the shear spinning specimen.

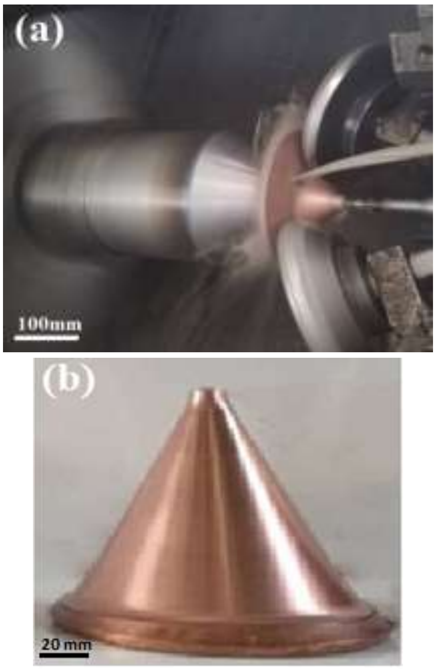

Fig. 4. (a) The shear spinning machine used and (b) the specimen was formed by shear spinning.

Metallography was performed on the shear spinning and rolling specimens according to ASTM E3. The location of the metallographic specimens was shown in Fig. 5. Their surface was polished with 220 to 3000 sandpaper and then polished.

The specimens were then etched in 150 cc Hcl +10 gr $Fecl_3$+ 100 cc H_2O solution, and then the specimens were examined under an optical microscope. The optical microscope used for metallography was Olympus BX. These measurements are based on the cross-line method and are obtained using Celemex software. The distribution of grains and grain boundaries was performed by electron back-scatter diffraction (EBSD) analysis on shear spinning and rolled specimens using the OXFORD instruments AZtecHKL EBSD system with ATEX software. Specimens were prepared for EBSD analysis after mechanical polishing by electro-polishing using 50 cc H_3PO_4 + 50 cc C_2H_5OH + 100 cc H_2O solution.

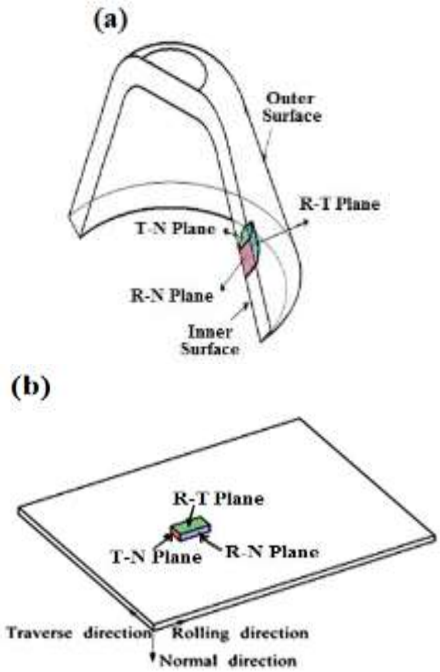

Fig. 5. Position and location of metallographic specimens on R-T, R-N and T-N planes in (a) the shear spinning specimen and (b) the rolled specimen.

To investigate the changes in strength and the relative elongation of the sheet under the forming process, the uniaxial tensile test was used. Tensile test specimens were prepared according to the ASTM E8M standard to investigate the difference between mechanical properties and anisotropy properties in three directions of 0º, 45º, and 90º compared to the forming direction. Fig. 6. and Fig. 7. show how the tension specimens are positioned in the 0º, 45º, and 90º directions, taking into account the forming direction. Anisotropy was also assessed using the ASTM E517 standard.

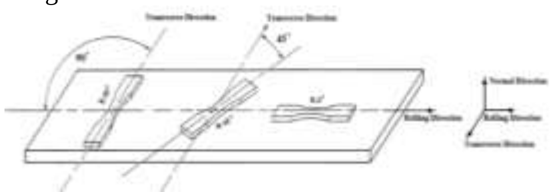

Fig. 6. Preparation of tensile test samples for rolled specimens in three directions 0º, 45º, and 90º.

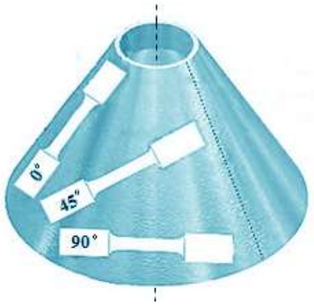

Fig. 7. Preparation of tensile test samples for shear spinning specimen in three directions 0º, 45º, and 90º.

The Vickers micro-hardness were performed in both shear spinning and rolling specimens accordance with ASTM 384 standard. The micro-hardness test was performed at the load of 100 g for 13 s duration time by using NOVOTEST micro indention device.

3. Results and Discussions

3.1. Microstructure

The microstructural pictures of the rolling and shear spinning specimens are shown in Fig. 8. and Fig. 9. in three different sections respectively.

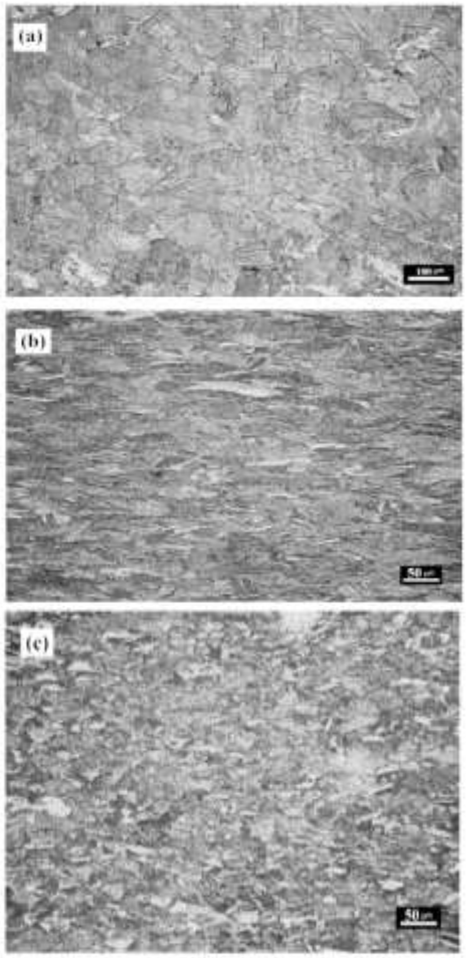

Fig. 8. Microstructural pictures related to the rolled specimen and in sections a) R-T plane and (b) R-N plane and (c) T-N plane.

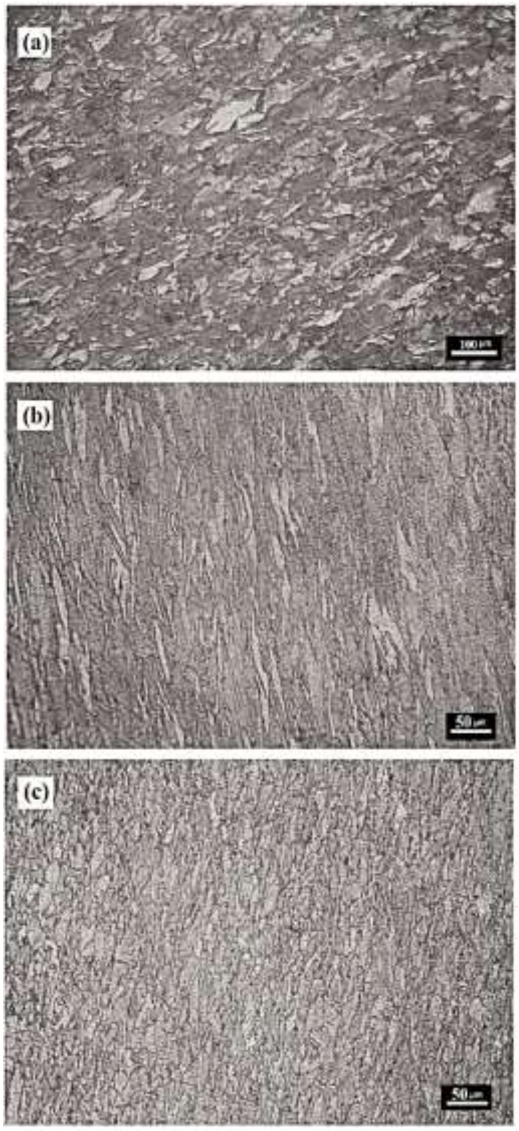

Fig. 9. Microstructural pictures related to the shear spinning specimen and in sections a) R-T plane and (b) R-N plane and (c) T-N plane.

Table. 2. shows the average grain size, grain length and width, and forming ratio on the R-T, R-N, and T-N planes. In rolled and shear spinning specimens, the grains are stretched based on the strain value and strain direction to form bands of different widths. As we know, dislocation slippage is the primary mechanism during plastic deformation, which leads to the formation of dislocation cells, dislocation walls, or micro-bands, depending on the strain applied and the initial orientation. Deformation bands have also been observed in Liu and Hansen [12] research. They found that the grains were divided into four macroscopic bands, called deformation bands (DBs), parallel to the rolling plane. Between the four bands, there are three transition bands in which the direction is constantly changing from DB to the adjacent band.

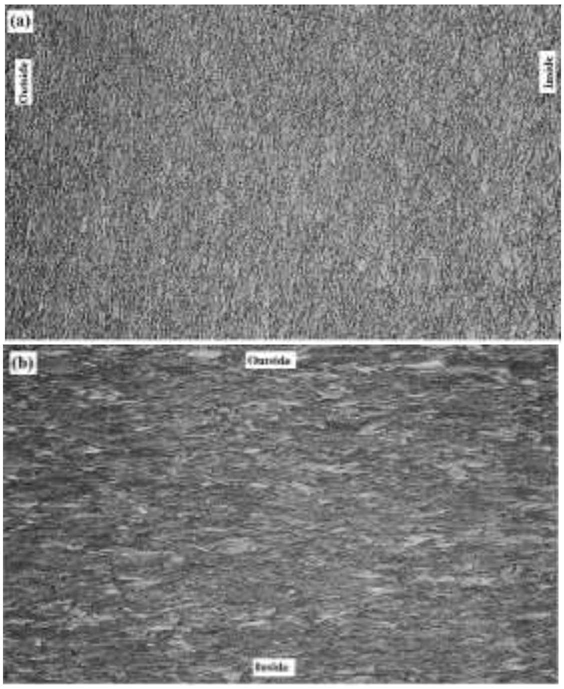

Fig. 10. Microstructure of specimens (a) shear spinning and (b) rolled.

Also, shear bands occur as a unique manifestation of local plastic instability at medium to large strains [13]. According to the microstructural pictures of Fig. 8. and Fig. 9. and the grain sizes obtained in Table. .2, it can be seen that by performing cold work such as rolling and shear spinning, the grain size is reduced and grains are stretched in the forming direction. In the shear spinning process, the grains are stretched in the axial direction and elongated in the circumferential direction. A similar type of microstructure has been observed in the research of Radović et al. [4]. Comparison of grain size in three planes R-T, R-N, and T-N in rolled and shear spinning specimens shows that the grain elongation in the rolled specimen in the R-N plane is more than in the shear spinning specimen, while in the shear spinning specimen, the grain elongation on the T-N plane is more excellent. It can be concluded that by performing the shear spinning process, the grains are stretched in both axial and circumferential directions.

In contrast, in the rolled specimen, the grains are elongated more in the rolling direction and compressed in the T-N plane.

This elongation of the grains in the microstructure has caused deformation bands. Shear bands are also visible in the microstructure.

These shear bands are higher in shear spinning specimens due to the nature of the shear forces introduced in the shear spinning process.

According to Fig. 10., it can be stated that another difference in the microstructure obtained from rolling and shear spinning of copper is that the microstructure, size and, form of the grains of the rolled specimen are more uniform compared to the shear spinning specimen. In shear spinning specimens, there is a difference between the outer regions (close to the roller) and the inner regions (close to the mandrel), and the grains close to the roller are smaller than the grains close to the mandrel. This microstructure heterogeneity has also been observed in the research of Wang et al. [14], Kubilay [15], Wardoyo et al. [16] and, Zhan et al. [9].

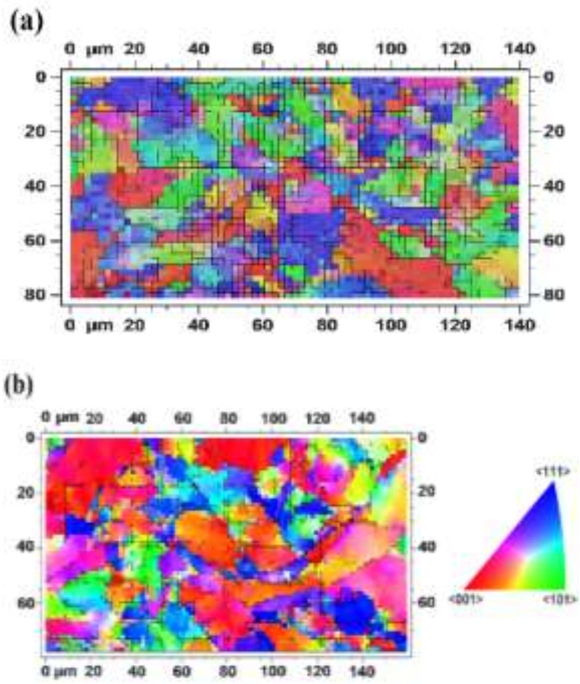

Fig. 11. Inverse pole figure (IPF) of specimens (a) rolled, and (b) shear spinning.

Table. 2. Average grain size and grain boundary distance in R-T, R-N, and T-N planes in rolled and shear spinning specimens.

Sample Name	R-T Plane			R-N Plane			T-N Plane		
	Length of (µm) Grain	Width of (µm) Grain	Aspect Ratio	Length of (µm) Grain	Width of (µm) Grain	Aspect Ratio	Length of (µm) Grain	Width of (µm) Grain	Aspect Ratio
Rolling	35.47	14.51	2.44	40.33	5.80	6.95	24.88	6.06	4.10
Shear Spinning	33.98	14.50	2.34	36.35	5.47	6.64	28.80	5.47	5.26

The EBSD orientation map of the two rolled, and shear spinning specimens is shown in Fig. 11. These pictures are taken from the T-N plane of rolled and shear spinning specimens. It should be noted that the pictures were taken from the center of the parts.
It can be seen that in the rolled specimen, the grains have a specific orientation and are mainly near the <111> direction, which indicates the rolling direction. In the shear spinning specimen, the grain orientation distribution is almost random, and the highest orientation is observed in the <111> and <001> directions. Deformation bands are visible in both specimens.

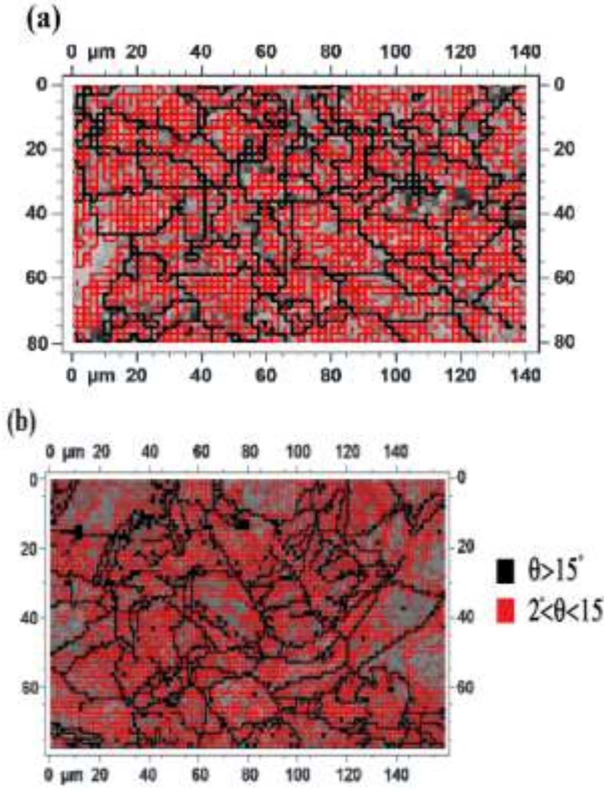

Fig. 12. High angle and Low angle boundary maps in specimens (a) rolled and (b) shear spinning.

Factors such as the amount of deformation, strain states, initial size, and geometry of the deformation area play an important role in the final texture and the expansion of the texture gradient [17]. Considering that the strain and the initial size were equal in both specimens, the difference in texture between the two rolled and the shear spinning specimens can be regarded due to the strain state, and the shear stresses applied to the shear spinning specimen.
The map of high-angle and low-angle grain boundaries in rolled and shear spinning specimens is shown in Fig. 12. Low angle boundaries are defined as misorientations boundaries $2° < \theta < 15°$ and high angle boundaries with misorientations $15° < \theta$. The ratio of high angle boundaries to low angle boundaries (HAGB/LAGB) is equal to (0.30/0.70) in the rolled specimen and (0.34/0.66) in the shear spinning specimen.
These results show that in the shear spinning specimen, the percentage of high angle boundaries is slightly higher than in the rolled specimen. This can be attributed to the more significant shear strain that enters the T-N plane in the direction of the T-D. Based on the EBSD pictures, it can be seen that the grain boundaries are formed in shear spinning along the geometrically necessary boundaries (GNB) for grain fragmentation.
In shear spinning, a large number of small sub-grains are developed. While in the rolling process, there are small angles of orientation between the GNBs in the DB that divide the grains, especially large grains, into regions with different directions during deformation.
Several twins have also been observed in the deformed structure, although the number of twins has been negligible.
Twins not only create independent slip systems during deformation but also causes the coarse grains to be cut into small grains. This was also observed in a study conducted by Wang et al. [14].
Cross-slip of dislocations and twins in materials with low stacking fault energy (SFE) such as copper is one of the most important deformation mechanisms [18]. There are different mechanisms of grain refinement in forming processes. Continuous dynamic recrystallization is one of the main reasons for fine-grain formation during cold work or warm work [19, 20]. The grains become fragmented by creating low angular dislocation boundaries due to deformation, followed by a gradual increase in their misorientation, eventually leading to their conversion to normal grain boundaries [21].
Zhao et al. [22] believe that grain refinement is achieved through the formation and division of micro-bands and thin lattice structures in the main coarse grains. Xia et al. [23] also stated that the reason for the evolution of microstructure during spinning could be considered as grain division. As a result of the high plastic deformation, the dislocations gradually increase inside the grains cellular structures.
These cellular structures become sub-grains by more plastic deformation. These sub-grains form independent grains with increasing angles of misorientation, and their boundaries become high angle boundaries. Also, the intersection of deformation bands (DBs) can lead to the grains division into multiple sub-grains.

3.2. Tensile test

The primary annealed, rolled, and shear spinning specimens were subjected to tensile tests. Tensile test was performed in three directions of 0°, 45°, and 90° relative to the forming direction. The tensile test results of the annealed and rolled specimens are shown in Fig. 13., and the shear spinning specimens are shown in Fig. (14).

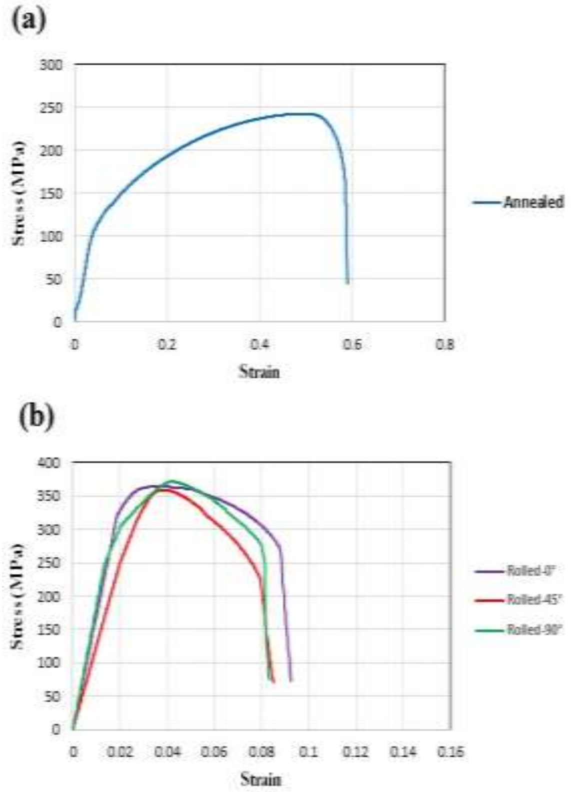

Fig. 13. Engineering Stress-strain curve of specimens (a) annealed prototype (b) rolled.

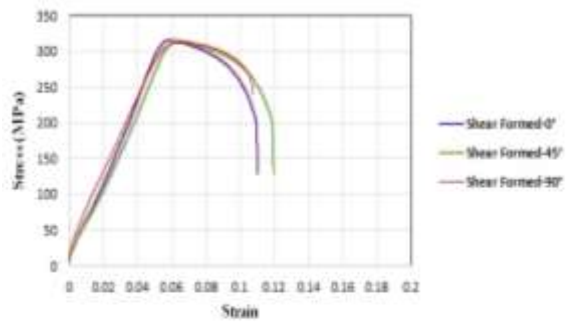

Fig. 14. Engineering stress-strain curve of a shear spinning specimen.

Comparison diagrams of strength and elongation in the rolling process and shear spinning process are shown in Fig. 15.a and Fig. 15.b As can be seen, cold rolling and shear spinning operations have increased the strength and reduced the elongation in all three directions of 0º, 45º, and 90º. This increase in strength and decrease in the elongation in different directions has also been observed in the research of Xu et al. [24].

The reason is related to increasing work hardening, increasing the density of dislocations, and decreasing the grain size [18]. According to Fig. 15., it is observed that the strength in all three directions of 0º, 45º, and 90º compared to the direction of forming in shear spinning specimens is less than rolled specimens, and the elongation is somewhat higher.

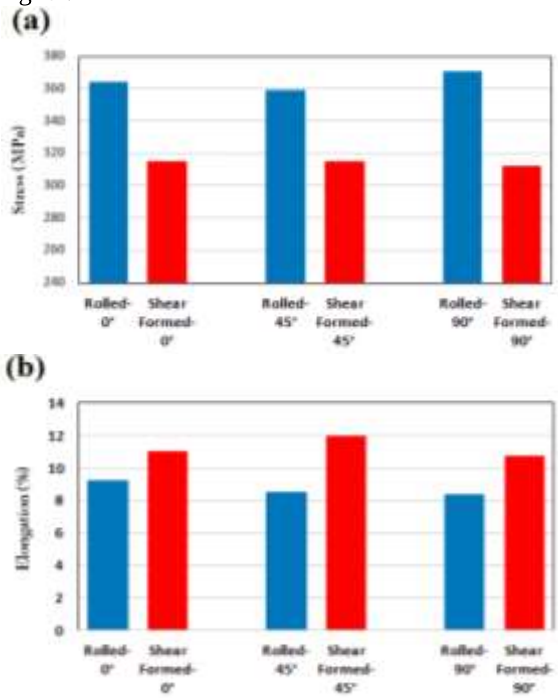

Fig. 15. Comparative graph of (a) tensile strength and (b) elongation in three directions of 0º, 45º, and 90º relative to the forming axis in shear spinning and rolling specimens.

In the shear spinning specimen, the strength in the axial direction is slightly more significant than the strength in the peripheral direction. This has also been mentioned in the research of Haghshenas et al. [18]. Also, the difference between the tensile strength in the three directions of 0º, 45º, and 90º compared to the forming direction in the shear spinning specimen is less than the rolled specimen and is close to each other (Table. 3.).

Table. 3. Anisotropy values of rolled and shear spin specimens

Sample name	ΔR	R_m
Rolling	0.3368	1.6530
Shear spinning	0.2025	1.6407

This can be related to the fact that in the microstructure of the shear spinning specimen, the grains were stretched in two axial and circumferential directions, and the grain elongation on the T-N plane in the shear spinning specimen was more than the rolled specimen. Anisotropy in shear spinning and rolled specimens are close to each other and shows little difference. Also, according to the obtained values, it shows that both specimens have anisotropy.

3.3. Microhardness Test

A micro-hardness test was performed on rolled and shear spinning specimens. The diagram of the results of the micro-hardness test in three different planes is shown in Fig. 16. Due to cold work and increased work hardening and density of dislocations, hardness has increased in rolled and shear spinning specimens. Grain refining is the most important reason for increasing micro-hardness [9]. There is not much difference between the micro-hardness values of the rolled and shear spinning specimens. The results obtained from the micro-hardness test on the R-T and T-N planes in both specimens are close to each other and slightly different, while the results of the micro-hardness on the R-N plane show more differences. This more significant difference can be attributed to the more grain refinement done in the rolled specimen on the R-N plane.

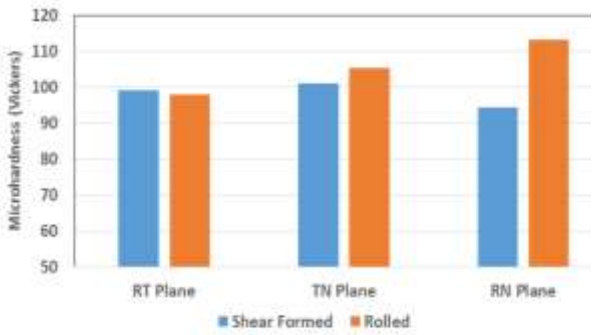

Fig. 16. Results of micro-hardness test in rolled and shear spinning specimens.

4. Conclusion

In this study, the microstructure and mechanical properties of two rolled and shear spinning specimens with 50% thickness reduction in C11000 copper metal were investigated and compared:

1- Due to the microstructure, grain refinement has occurred in both rolled, and shear spinning parts and deformation bands have been created in the microstructure.

2. In the shear spinning specimen, the grains are stretched in the axial direction and elongated in the circumferential direction. The increase in grain length on the T-N plane is more significant in the shear spinning specimen than in the rolled specimen.

3. The strength of the shear spinning specimen is lower than that of the rolled specimen, and the elongation is higher. The anisotropy in the shear spin specimen is less than the rolled specimen.

4. The difference in mechanical properties in the shear spinning specimen compared to the rolled specimen in three directions of 0º, 45º, and 90º is less than the forming axis.

5. According to the results of this study, it can be stated that the microstructure and mechanical properties of the two specimens of rolled and shear spinning are somewhat close to each other and there is not much difference.

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