# Effect of Twist Extrusion Process on the Mechanical Properties and Microstructure Evolution of 70-30 Brass Alloy

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## ABSTRACT

In this study, cartridge brass alloy was severely deformed by twist extrusion (TE) technique and its mechanical properties, before and after TE, was investigated using a die with the twist line slope of $\beta = 30°$. It was revealed that large strains imposed on the material by this advanced method of severe plastic deformation (SPD) led to a nano-scale ultrafine microstructure and to an enhancement of the mechanical properties. It was revealed that the more TE passes a finer grain sized microstructure obtained. Also, by increasing the number of TE passes, the yield strength and ultimate tensile strength increased. Microhardness test results show that the hardness increases from 55 (initial sample) to 110 HV and 140 HV in the center and lateral edges of the sample pass #1 TE, respectively. After six passes of twist extrusion, the microhardness of the center and lateral edges of the sample reaches 160 HV.

## 1-Introduction

Organic colorants have become an inevitable part of our life. Synthetic dyes have replaced natural types in paper, clothes, drugs, and even food industries. However, the waste of these materials is considered as pollutant and dye treatment has become a scientific challenge. The membranes, adsorbent, floated foams, and coagulation agent are usually applied to remove the pollutants. These methods are not efficient and exert side effects. Oxidation of pollutants is a modern method with high efficiency and without any destructive effect. A method entitled "*advanced oxidation process (AOP)*" has been developed. The photocatalytic reactions provide the required conditions of AOP; therefore, the semiconductor materials are identified as suitable agents for AOP [1].

Cu due to its unique properties, including attractive colors, excellent electrical and thermal conductivity and ductility in cold and heat, is widely used in various industries [1]. But an important problem with the use of Cu equipment is the low wear resistance of this metal [2]. On the other hand, in many applications, such as marine industries, higher corrosion resistance is also required [3]. For this purpose, various surface treatments such as laser surface cladding, plasma surface process, thermal spraying, chemical, and physical deposition are used[4-7]. Among them, the electroless coating, which was invented by Brenner and Riddel in 1946, is the most important method for coating

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In recent years, manifestation of severe plastic deformation (SPD) methods in material science has shed light on new prospects in achieving a unique combination of high strength and ductility [1] as well as attaining ultrafine-grained materials with improved properties. Several different SPD techniques are now available; these include high-pressure torsion (HPT) [2], equal channel angular pressing (ECAP) [3], multi directional forging (MDF) [4], accumulative roll-bonding (ARB) [5], simple shear extrusion (SSE) [6] and twist extrusion (TE) [7, 8]. Each process has unique properties determining its use in research and practice.

Twist extrusion (TE) is known as one of rather newly developed SPD methods which comply with strain accumulation and intense grain refinement to nano-scale sizes while the procedure is comparatively inexpensive. The key idea in TE is based on pressing out a pseudo-prismatic specimen through a die with a longitudinal profile consisting of two prismatic regions separated by a twisted part. Each cross-section of a billet undergoes severe shear deformations at the distorted region such that first, it is twisted by being deformed at a given angle in one certain direction, and then is re-twisted at the same angle in the opposite direction. TE is performed under high hydrostatic pressure in the center of deformation. The pressure is created by applying backpressure to the specimen when it exits the die. It is possible to produce more isotropic and homogeneous deformation by turning the samples 90° in each consecutive deformation or alternatively, make the use of consecutive clockwise–anticlockwise–clockwise twists. This matter is very important for electronic and magnetic materials. A comparison between TE and the two most widely used SPD methods, ECAE and HPT, reveals that firstly, TE provides some advantages over ECAE such as the ability to extrude the hollow parts and the rectangular cross-sections [1]. Secondly, HPT involves order of magnitude higher pressures than in any other SPD process which provides attainment of uniquely high strains and formation of ultrafine grained structures. However, application of HPT is limited to laboratory conditions due to small size of the samples. Ranjbarbahadori et al. [10] studied the effects of different routes for two pass TE (clockwise–clockwise or clockwise–counterclockwise rotation) of AA8112 aluminum alloy. Vakili Noor et al. [10] investigated the inhomogeneity and microstructural changes due to different routes of the TE process on pure copper. Shpak et al. [11] used the twist extrusion process for fabrication of nanostructured $Al_{86}Gd_6Ni_6Co_2$ bulk alloy from amorphous melt-spun ribbons. The TE process helps the transition from an amorphous state into the crystalline. Ranjbarbahadori et al. [12] studied the effect of different SPD processes (TE and equal channel angular pressing (ECAP)) on the mechanical properties and microstructure of pure copper alloy. In TE, strain distribution along the cross-section of the specimen is inhomogeneous; getting away from the axe, plastic strain increases, thus, the grains being finer. The microstructural inhomogeneity leads to inhomogeneities in the mechanical properties of the composite; the central area of the cross section having lowest strength. It is expected that with increasing the number of TE cycles, the microstructure becomes uniform [13].

In the present research, microstructural evolution of 70-30 brass alloy which was severely deformed by twist extrusion, and grain refinement behavior of the material due to accumulated strains were studied. The effect of number of TE passes on strength, ductility and hardness of the alloy were also investigated

## 2. Materials and Methods

Cartridge Brass (C26000, Cu-30Zn) was selected for experimentation. Table 1 shows the chemical composition of the samples obtained from quantometer analysis. The sample section was a 12 mm ×12 mm square section. The length of the samples was equal to 130 mm. For elimination of previous work hardening, the samples were held at 450°C temperature for 3 hours and cooled in the furnace to produce full annealed samples. The twist angle of the TE die is equal to 30°. $MoS_2$ lubricant was used to decrease the friction between the samples and the die. The sample is pushed through the die using a 2.5 ton hydraulic press with a constant speed of 3 mm/s.

**Table 1.** Chemical composition of 70-30 brass alloy (wt%) used in this work.

| Cu | Zn | Sn | Si | Pd | Fe | Ni | Al | P | Mn |
|---|---|---|---|---|---|---|---|---|---|
| 70.112 | 29.83 | 0.004 | 0.001 | 0.01 | 0.02 | 0.009 | 0.001 | 0.002 | 0.001 |

To investigate the microstructural changes in the material due to twist extrusion through micrography, the samples were prepared by cutting them from the cross-section perpendicular to the axial direction of the extruded billets. The microstructure of the annealed and twist extruded samples was investigated using a CAMSCAN MV2300 scanning electron microscope (SEM) equipped with a TESCAN VEGAII EDS analyzer. The samples were prepared by electro-polishing with a STRUERS LECTRO pol-5 machine. Phosphoric Acid 20% was used in the electro-polishing process. The applied voltage was 24V and it is applied for 8 seconds into the samples. Also, chemical etching was applied on the samples and the microstructure was observed using a scanning electron microscope. The etchant solution was prepared by combining 20 ml Acetic Acid + 10 ml $Cr_2O_3$ 5% + 5 ml $FeCl_3$ 15% + 100 ml distilled water. Etching time was in the range of 5-15 seconds to observe the microstructure briefly.

Mechanical properties of the twist extruded and annealed samples were compared using a tensile test. Also, the samples are cut perpendicular to the extrusion direction and the hardness variation was measured along the width of the cross section. The Vickers microhardness method was implemented for measurement. The applied load was equal to 200 g. The tests were repeated three times and the average of the results was reported.

## 3. Results and Discussion

Figures 1 and 2 show the observed microstructure for the center and lateral edges of the TE and annealed samples.

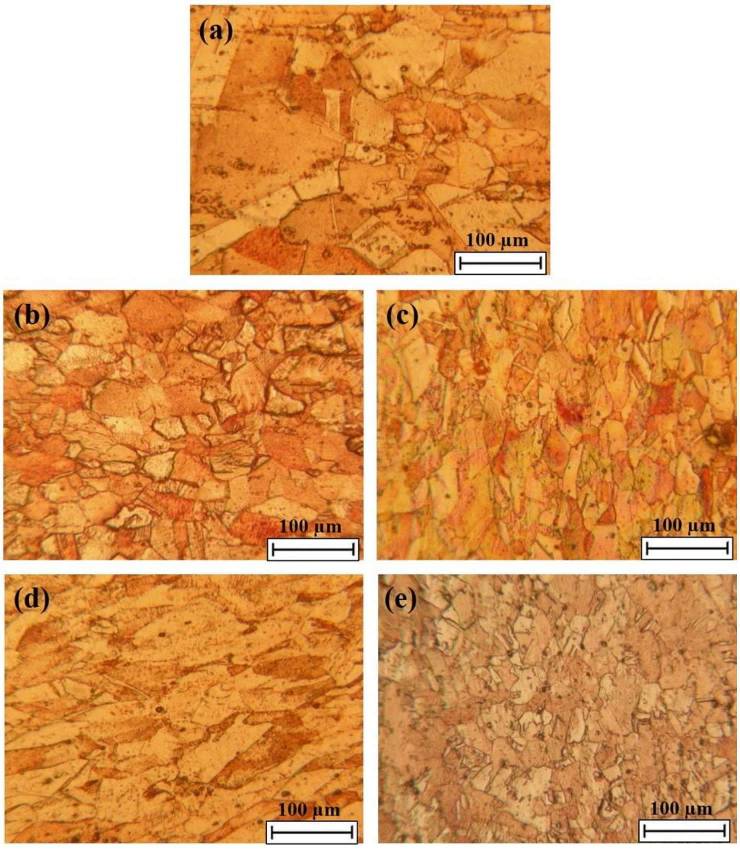

**Fig. 1.** Microstructure at the center of a) annealed b) pass #1 c) pass #2 d) pass #4 e) pass #6 TE sample (1000x mag).

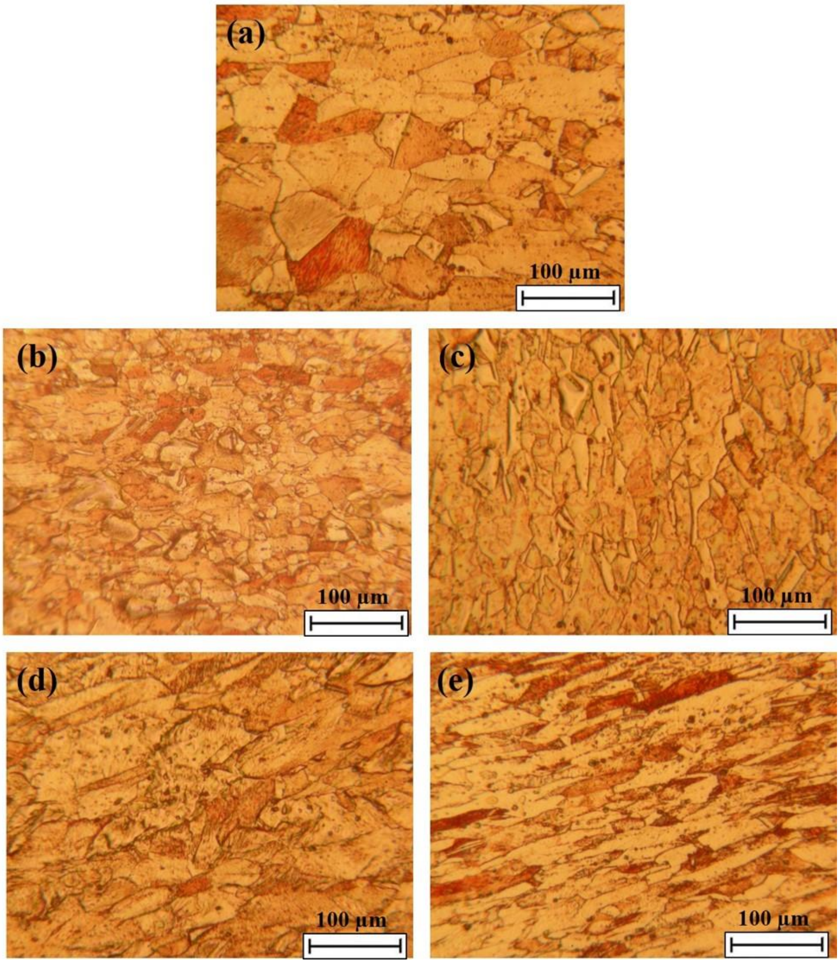

**Fig. 2.** Microstructure at the lateral edge of a) annealed b) pass #1 c) pass #2 d) pass #4 e) pass #6 TE sample (1000x mag).

By increasing the number of TE passes, the average grain size will be decreased. The microstructure was therefore, more homogenized in the lateral regions of the cross-section than the central regions. This is the evidence that the lateral regions undergo larger strains compared to the central regions [9], that is, strain value in radial direction increases from the center of the cross-section towards the edge. The true strain values in different parts of the cross-section were obtained using the relationship:

$$\varepsilon = \ln\left(\frac{d_0}{d_1}\right)^2 \qquad (1)$$

where $d_0$ and $d_1$ are the average diagonal before and after TE process, respectively. It should be added that strain distribution at deformation zones is strongly dependent on the geometry of the die profile, that is, deviation angle (β) and rotation angle (α) and one can change the strain intensity at different deformation zones by changing these factors [13].

In severe plastic deformation, the existence of crystal defects in the vicinity of grain boundaries causes generation of high elastic stresses, especially at high dislocation densities [14]. In addition, the researchers [15, 16] showed that in materials with high stacking fault energy (SFE), repeating the severe plastic deformations leads to finer grain sizes and a more homogenous microstructure. In the twist extrusion process, the grain size decreases by increasing the number of TE passes. In 70-30 brass alloy, the Zn atoms construct a solid solution in copper base-metal. By repeating the severe plastic deformation process, the recovery rate and consequently the slip of dislocations will be decreased due to the existence of Zn atoms in the microstructure. This will cause a delay in access to the homogenous and ultrafine grain sized microstructures. The average grain size was reduced from 100 μm to 10 μm after twist extruding the sample up to six passes. Also, Figures 1 and 2 show that the grain refinement happens more at the lateral edges. This implies that the lateral edges experienced higher strains than the center of the sample while twisting in the channel. The outer edges had the longest distance from the rotation center in the twist extrusion process. As the distance decreases, the deformation strain value was reduced.

Figures 3 and 4 show an SEM image of the center and lateral edge of the sample. Two main mechanisms of the plastic deformation are slipping and twinning. Twinning usually happens due to applying mechanical stress and the orientation of atoms changes in such a way that the distorted part becomes a mirror image of the other part. The important role of twinning in plastic deformation is that it causes changes in the plane orientation so that further slip can occur. The twins produced by severe plastic deformation and grain refinement are visible in Figures 3 and 4 as parallel dark striations. In addition, intra-granular twins are shown by red arrows. The numbers of twins are increased by repeating the TE passes.

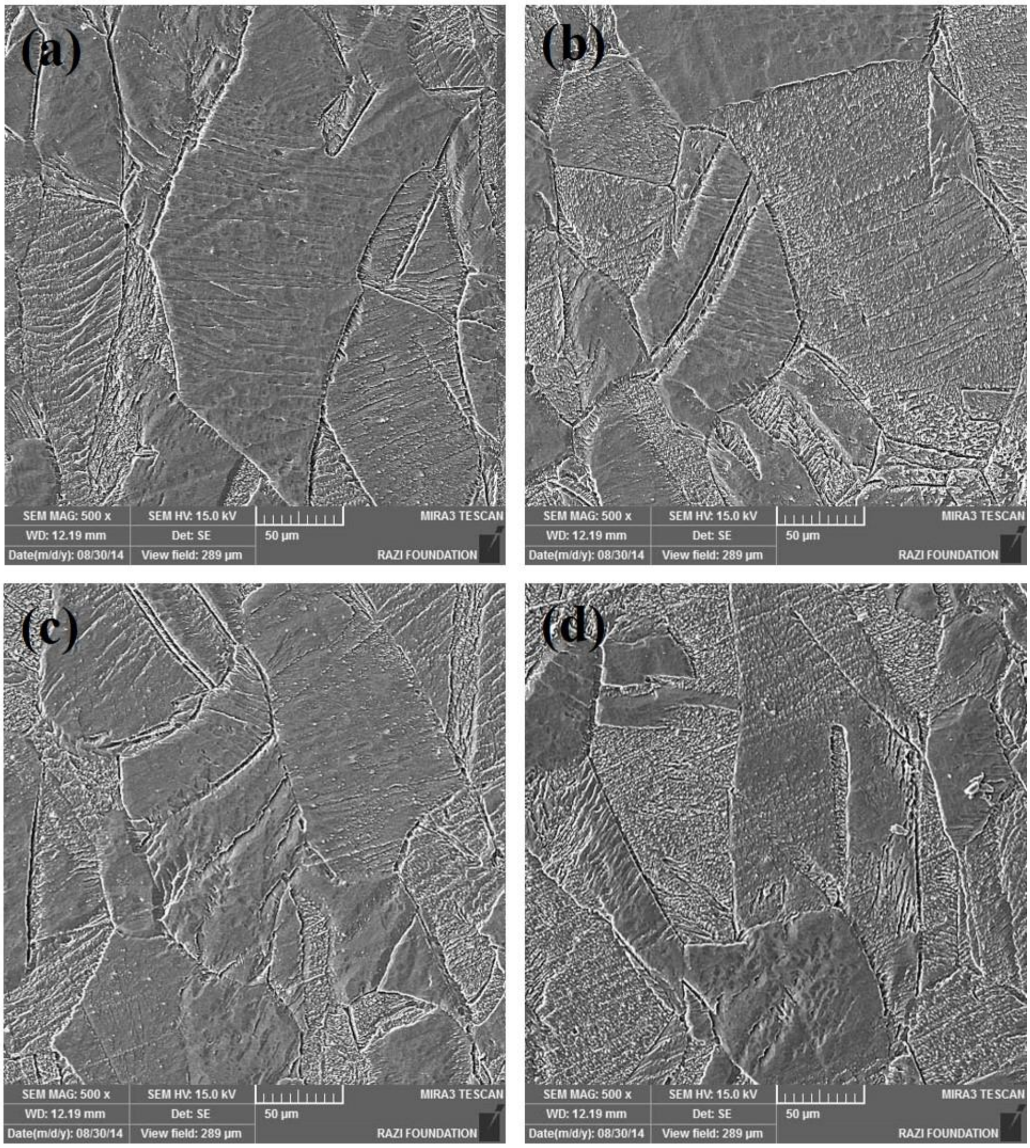

**Fig. 3.** SEM image at the center of a) pass #1 b) pass #2 c) pass #4 d) pass #6 TE sample (500x mag).

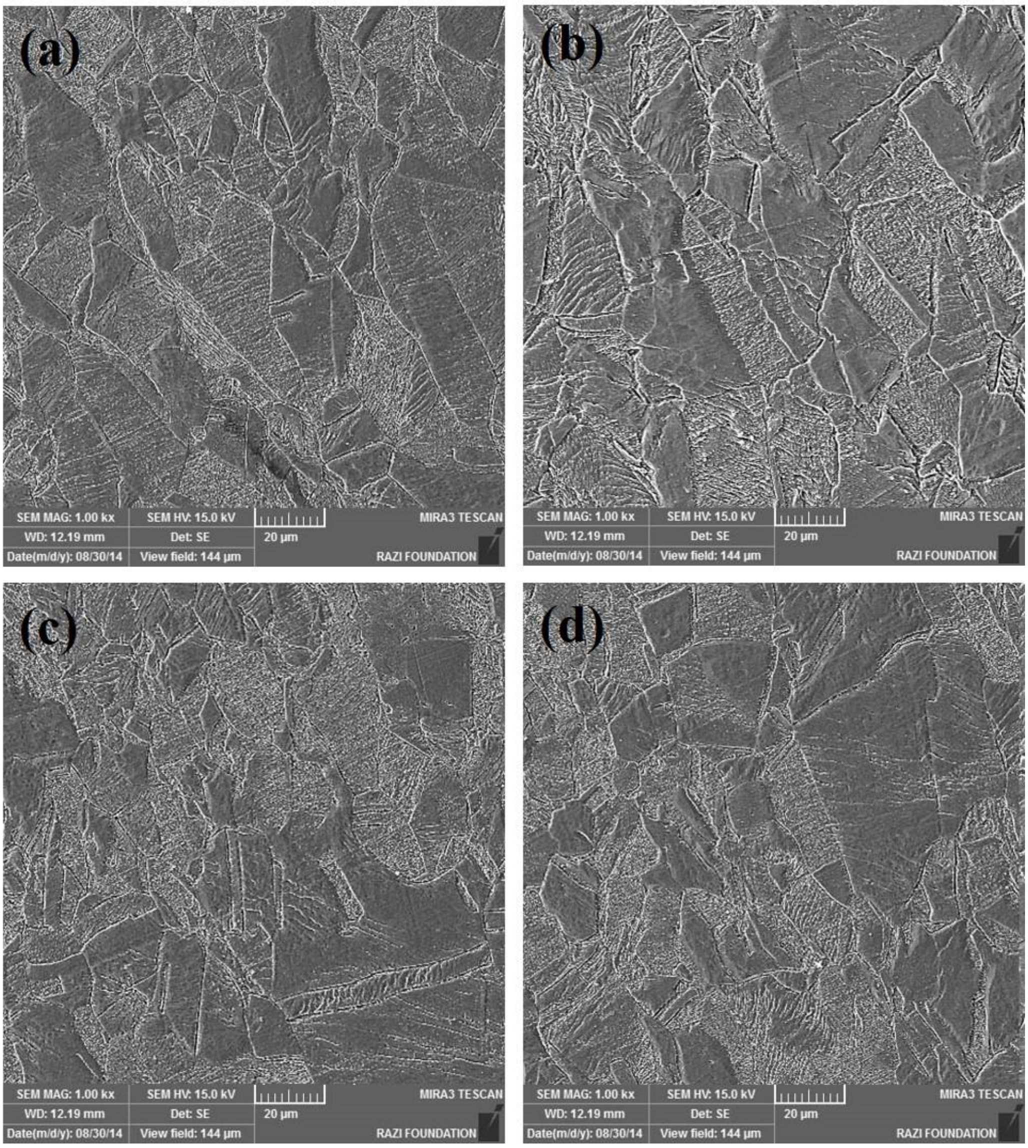

**Fig. 4.** SEM image at the lateral edge of a) pass #1 b) pass #2 c) pass #4 d) pass #6 TE sample (1000x mag).

Figure 5 shows the engineering stress-strain curve for annealed and multi-pass twist extruded samples. By analyzing the results of a tensile test, the variation of yield strength, ultimate tensile strength and maximum elongation are shown in Figure 6. The yield and ultimate tensile strength of the annealed sample were equal to 101 and 211 MPa respectively. The size of the plastic deformation (work hardening) zone decreased for the multi-pass TE process. The yield and ultimate tensile strength was increased due to dynamic recrystallization while implementing SPD processes. The maximum increase in mechanical properties occurs after pass #1 TE. The yield and ultimate tensile strength were increased to 230 and 325 MPa (127% and 54% increase) respectively. After pass #6 TE, the yield and ultimate tensile strength are increased to 330 and 426 MPa respectively. The maximum elongation of samples is decreased from 63% for the annealed sample to 41% for pass #1 TE and then 19% for pass #6 TE. As the number of passes increases, the maximum elongation was reduced due to applying higher strains in the multi-pass TE. This applied deformation changes to the microstructure non-uniformly.

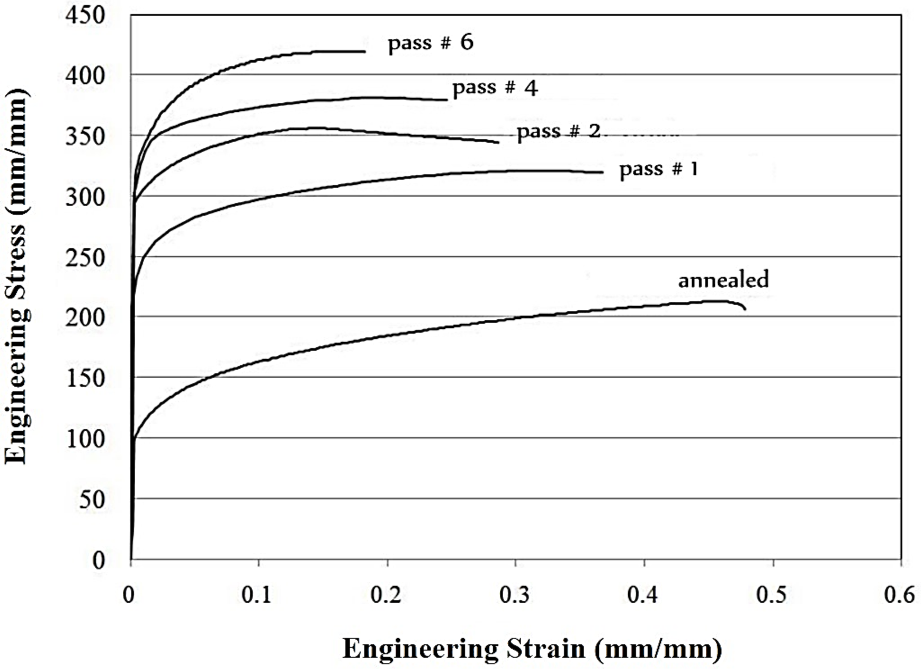

**Fig. 5.** Engineering stress-strain curve of annealed and twist extruded samples.

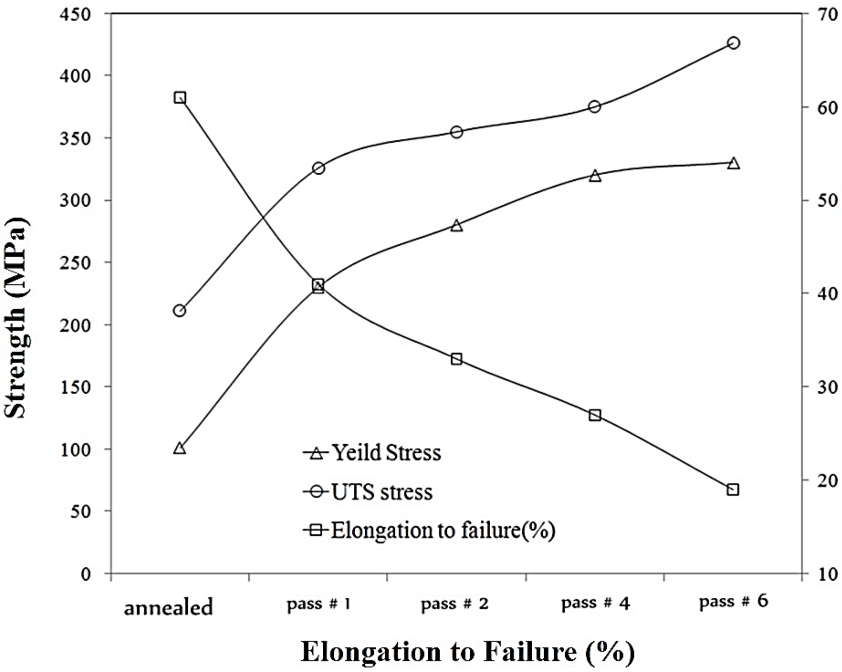

**Fig. 6.** Variation of tensile properties due to multi-pass TE process.

The TE-processed brass alloy show high strength but limited total elongation. It should be noted that many NC steels produced via SPD processes often: (i) exhibit low total elongation at room temperature; (ii) the total elongation is typically less than a few per cent; (iii) the regime of uniform deformation is even smaller. In general, the extraordinary increase in the strength values of UFG alloys processed by SPD is assumed to be primarily from the considerably refined microstructure consisting mainly of HAGBs (grain size strengthening) and the high dislocation density (dislocation strengthening) [17, 18]. Limited ductility after TE is due to the decreased strain hardening capacity of severely deformed brass alloy that leads to the early onset of necking.

Figure 7 shows the results of the Vickers microhardness test for the TE samples. The hardness of the annealed sample at the center and lateral edges was uniform and equal to 55 HV. The hardness increased to 110 and 138 HV at the center and lateral edges after pass #1 TE. The hardness at the center of the sample was lower than at the lateral edges. The maximum increase in hardness occurs in pass #1. The hardness was increased for the next passes of TE. The hardness becomes uniform again at the center and lateral edges of the sample after six pass of TE. The strain was higher at the lateral edges but the hardness tends towards a saturation value as high as 160 HV for pass #6 TE. Thus, the homogeneity was increased at the lateral edges and in the center of the sample. Despite the lower stress magnitude at the center of the sample, the hardness was increased by increasing the number of TE passes.

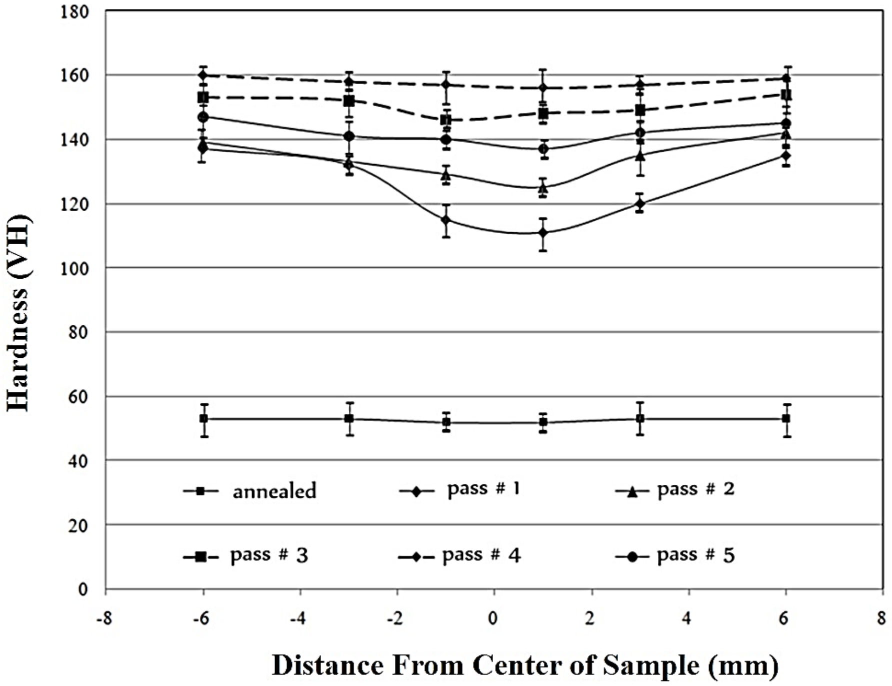

**Fig 7.** Variation of microhardness due to multi-pass TE.

## 4. Conclusion

In this article the effect of the twist extrusion process on mechanical properties and microstructure of 70-30 brass has been investigated. The main findings of this research can be summarized as follows:

1. The average grain size was reduced by increasing the number of TE passes. However, the ultrafine grain structure is not accessible in 70-30 brass because of a decrease in the recovery rate and slip of dislocations. After pass #6 TE, the average grain size equals 10 μm.
2. SEM imaging showed activation of the twinning mechanism due to the TE process.
3. The yield and ultimate tensile strength increased from 101 and 211 MPa (annealed sample) to 330 and 426 MPa after pass #6 TE, respectively.
4. The microhardness test results showed that the maximum increase in hardness occurred in pass #1 TE. In addition, the microhardness changed from 55 HV (annealed sample) to 110 and 138 HV at the center and lateral edges after pass #1.
5. The microhardness was increased by repeating the TE process. After six passes of TE the microhardness profile was uniform at the center and lateral edges of the sample.

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