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INFLUENCE OF DIFFERENT TORSION PITCH ON MICROSTRUCTURAL EVOLUTION AND STRENGTHENING MECHANISM OF Al WIRES

This paper focused on the effect of pure torsion deformation and various torsion pitches on the mechanical properties of the commercial pure Al wires which has not been examined so far. The initial wires with diameter of 4 mm have been torsion deformed to different pitch length (PL). In order to investigate the effect of gradient microstructure caused by torsion deformation, three different pitch length of 15 mm, 20 mm and 30 mm are considered. The results revealed that the level of grain refinement is correlated with the amount of induced plastic shear strain by torsion deformation. For the wire with pitch length of 15 mm, the grain sizes decreased to about 106 μm and 47 μm in the wire center and edge from the initial size of about 150 μm of the annealed wire. The micro-hardness measurement results show a gradient distribution of hardness from the wire center to the wire surface that confirmed the increasing trend of plastic shear strain obtained by FE simulations. The hardness of annealed sample (35 HV) is increased up to 73 HV at the wire surface for the smallest pitch length. The yield and ultimate tensile strength of the torsion deformed wires are also increased up to about 85 MPa and 152 MPa from the initial values of 38 MPa and 103 MPa of the annealed one respectively while the maximum elongation reduced significantly.

Keywords: Torsion deformation, tensile test, micro hardness, microstructure, Al wire

1. Introduction

Al wires with different diameters have extensive application in many industries, especially electric power transmission industry. These wires are of primary ingots that are large in diameter and then by numerous wire drawing process will reach to a desired dimension. Pure Al wires especially from 1xxx series of Al wrought alloys are not heat treatable and conventionally strengthened by work hardening and refining coarse grains to fine grains via repeated metal forming processes such as rolling and drawing [1]. During past decades, several severe plastic deformation (SPD) methods are developed in order to enhance the mechanical properties of commercial pure Al alloys [2]. Among them equal channel angular pressing (ECAP) [3-5], high pressure torsion [6-9] and accumulative roll bonding (ARB) [10] are widely used and examined. The main limitation of the mentioned methods is the small dimensions of the processed sample which restricted their usage.

Recently, it has been shown that the mechanical properties of metals could be improved by changing the strain paths[11,12]. Imposing pre-compression [13], pre-tension [14] and pre-rolling [15] are also reported.

Pure and combined torsion deformation is successfully used as a kind of SPD method to impose large plastic shear strain to different metallic materials[16-21]. Recently, some authors reported different changes in the strength of a raw material due to pure torsion deformation [17,19-22]. Guo et al. [22] studied the influence of pre-torsion deformation on the microstructure and properties of cold drawing pearlitic steel wires and they showed that the strength of processed wires reduced. But it is shown that by increasing pre-torsion strain, the tensile yield strength of commercial pure copper increases significantly due to the gradient lamellar dislocation substructures [21].

In comparison to the other pre-deformation methods, pre-torsion will not affect the dimension of samples and can be done for cylindrical section materials. on the other hand, the effect of pre-torsion (PT) deformation on the mechanical properties of commercial pure Al-wires has not been studied. The main purpose of this study is to evaluate the influence of torsional deformation on subsequent tensile properties of commercial pure Al wires. The results indicate that the yield and ultimate tensile strength of Al wires can be enhanced significantly by pre-torsion deformation.

2. Material and experimental procedures

2.1. Material

Commercial pure Al wires (99.5%) with a diameter of 4mm were examined in this study. The initial samples were cut directly from an as received cable to a length of 200 mm. In order to

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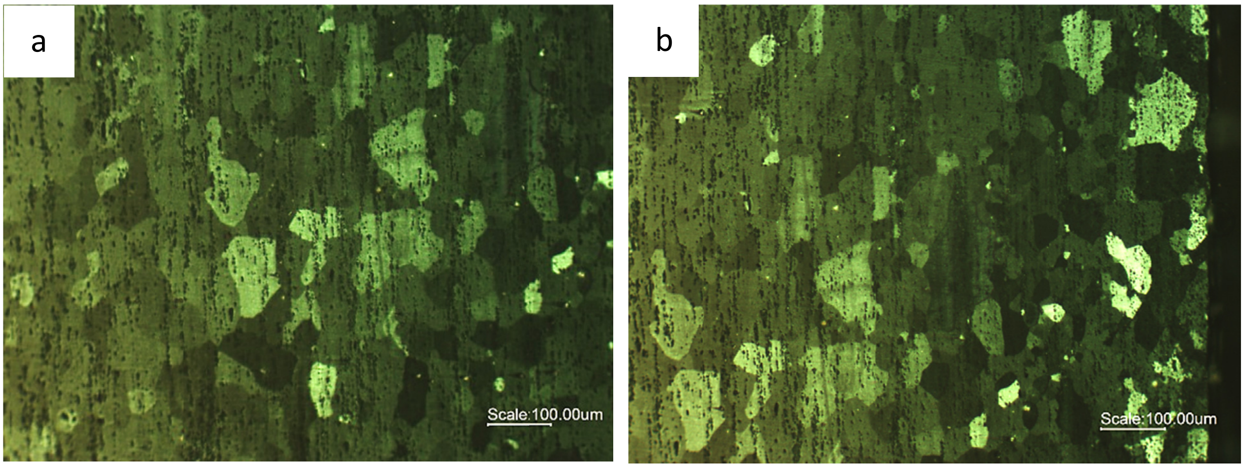

Fig. 1. Uniform microstructure of the annealed samples, a) center and b) surface

isolate the impact of previous work hardening, samples were kept for 1 hour at 400°C followed by furnace cooling [1]. After the annealing treatment, the average grain size of wire would be uniform equal to 140 µm both in the center and the surface zone as shown in Fig. 1. The stress-strain curve of the annealed wire is shown in Fig. 2.

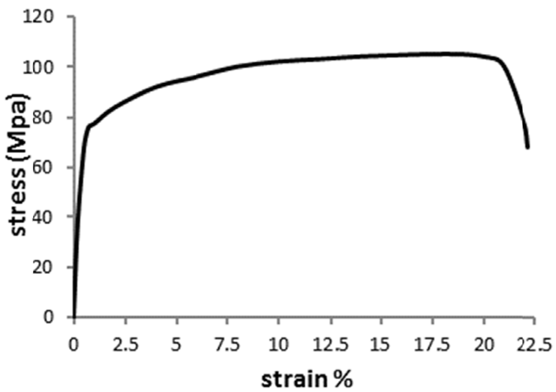

Fig. 2. Stress-strain curve of the annealed sample

2.2. Experimental procedures

A schematic view of torsional deformation process of the wires is shown in Fig. 3. A standard torsion testing machine was employed to apply different torsional revolutions to the wires at room temperature. A straight line painted along the longitude axis of the samples with a specific length of 150 mm. the other parts of the wires was grabbed and fixed in to the machine's clamps. The samples were considered to undergo different number of torsional revolutions such as 5, 7.5 and 10 rounds with the pitch length (PL) of 30 mm, 20 mm and 15 mm respectively (the wires can survive at least 12 torsional revolutions before fracture happened). All of the samples were twisted under 2 rpm speed of torsion testing machine. Also a 1 MPa tensile stress applied on the fix side to prevent wrinkles along the length of the wires during the deformation. Equation 1 can be used to calculate the amount of imposed plastic shear strain by the torsion deformation [23]:

$$\gamma = \frac{2\pi RN}{L} \tag{1}$$

where R is distance from the center of the axis, N is the number of torsional revolutions and L is the length of the deformed wire. The equivalent plastic strain cab be calculated by the following equation:

$$\varepsilon = \frac{(\gamma)}{\sqrt{(3)}} \tag{2}$$

The specified 150 mm length of wires was twisted between the clamps of torsion testing machine. The painted lines will ensure a uniform deformation along the axis of samples and it

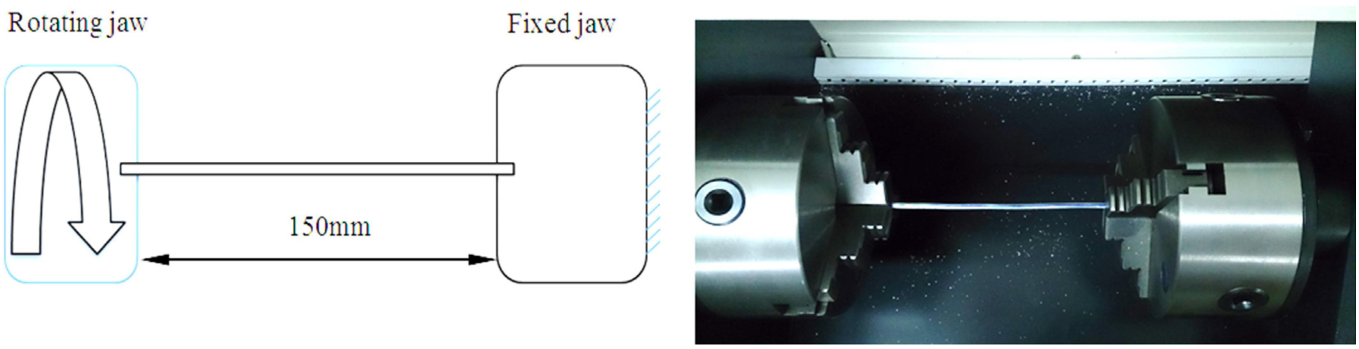

Fig. 3. Applying torsion deformation on specified 150 mm length of the wires with the aim of torsion testing machine

will help to measure the exact pitch length of the twisted wires. The calculated amounts of induced plastic strain of each sample are presented in Table 1.

TABLE 1

Pitch length and corresponding strains of different samples

Sample	Number of torsional revolution	Pitch length [mm]	Shear strain	Equivalent strain
PL 30	5	30	0.418	0.242
PL 20	7.5	20	0.62	0.36
PL 15	10	15	0.83	0.48

To compare torsion deformation with the wire drawing process, an annealed wire has been drawn to a diameter of 3.8 mm from initial diameter of 4 mm. In this case, the amount of induced equivalent plastic strain would be equal to 0.1. An another sample has been torsion deformed to the same amount of imposed equivalent plastic strain. The microstructure evolution and mechanical properties of the two samples have been compared with each other. Tensile tests were performed at room temperature at a strain rate of 0.0003 s^{-1} according to ISO 6892:1998 standards [24]. For each twisted wire with certain pitch length of torsion deformation, three tests were done to validate the results. The yield strength (σ_y) was measured as 0.2% proof stress. The Vickers microhardness testing were carried out with a load of 200 gf maintained for 10s according to ISO 6507-1:2005 standards [25]. Each microhardness value is the mean of 6 or more indentations placed along the wire axis direction.

Microstructure evolution of the wires after torsion deformation was investigated by optical microscopy under polarized light. Samples were cut from the near surface and near center region of the deformed wires. The samples are grinded using SiC papers and finally was polished by the use of 1 μm and 0.3 μm Alumina powder. Then, the samples were electrochemically etched using Barker's reagent. The microstructure of both near surface and near center region of the wires were examined as schematically shown in Fig. 4. The processed samples after applying different torsional revolutions are illustrated in Fig. 5.

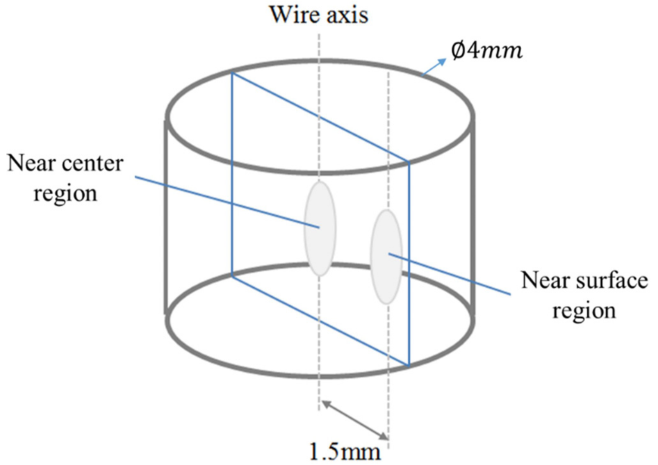

Fig. 4. Schematic illustration of longitudinal section of wire for microstructure study and microhardness measurements

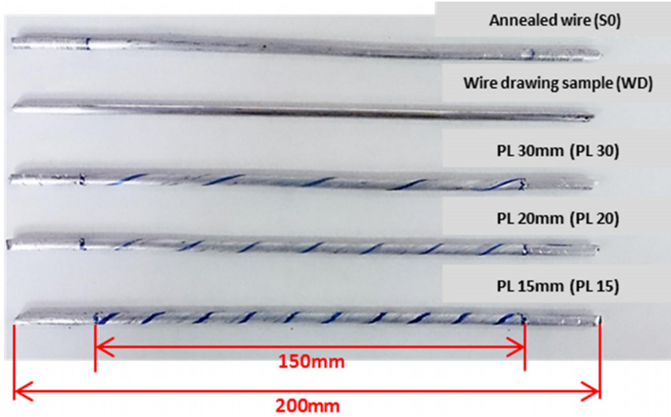

Fig. 5. Annealed sample, wire drawing sample and samples after torsion deformation

3. Results

3.1. Tensile test

The stress-strain curves of the deformed wires are shown in Fig. 6. Also the change in ultimate tensile strength after different number of torsional revolutions is illustrated in Fig. 7. The results show that by increasing the number of torsional revolutions, the yield and ultimate strength of Al wires increase. In addition, a significant change in tensile strength can be seen compare to the annealed wires. It can be seen that by 10 round twisting of specimens (PL of 15 mm), the ultimate tensile strength of Al wires increase about 50% while the maximum elongation decreases from 22% to less than 3%. In addition, the yield strength increases to about 85 MPa in comparison to the 38 MPa for the annealed wire (the yield strength was measured as 0.2% proof stress). The results indicate that the stiffness of Al wires is very sensitive to torsion deformation. As shown in Fig. 6, it can be seen that by imposing a small amount of plastic shear strain by torsion deformation the elongation of the processed wires is strongly decreased.

the elongation of Al wires is very sensitive to torsion deformation. It can be seen that the elongation of Al wires decreases strongly with only small amount of torsion strain.

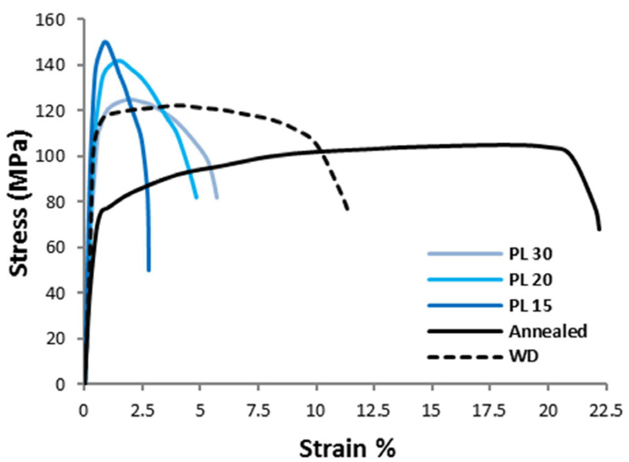

Fig. 6. Stress-strain curves of deformed wires

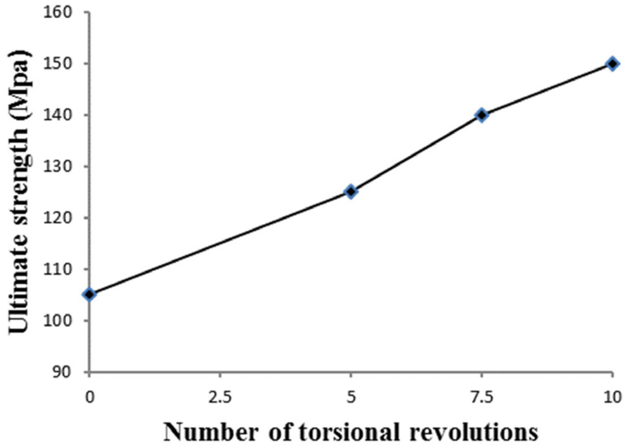

Fig. 7. Enhancing the ultimate strength due to number of torsional revolutions

As shown in Fig. 6, after 1 pass drawing of an annealed sample, the ultimate strength of wire increases to 120 Mpa, which is very close to ultimate strength of 5 round twisted wire (PL = 30 mm). But it should be noted that the elongation of the drawn wire is about 12% compared to 5.8% for the wire with PL of 30 mm. In higher number of torsional revolutions, the ultimate strength of twisted wires is much higher than the drawn one. Also by wire drawing process the diameter of wire reduces according to die exiting diameter, but during the torsion deformation the plastic shear strain induced to the wire without any cross sectional reduction. The corresponding properties obtained from Fig. 6 and Fig.7 are tabulated in Table 2.

TABLE 2

Mechanical properties of annealed and deformed samples

Sample	Tensile yield strength [Mpa]	Tensile ultimate strength [Mpa]	Elongation [%]
Annealed	38	103	22
PL 30 mm	59	120	5.4
PL 20 mm	74	140	4.8
PL 15 mm	85	152	2.8

3.2. Microhardness

By measuring the hardness in different positions from center of wire, we can examine the influence of torsional strains applied on specimens. Measurements show that by increasing the number of torsional revolutions, hardness in surface and center of wire increases too. The results of microhardness tests are shown in Fig. 8. Interestingly, hardening behavior occurs in the surface and center simultaneously. Also it can be seen that there is a difference between the hardness of center and surface of the deformed wires. While the hardness in center and surface of annealed wires are even. It should be noted that the variation of hardness occurs mainly at low strain levels. The hardness changes sharply at low strain stage but as the torsion strain increasing, the hardness increases slightly. The results indicate that the torsion deformation not only result in the variation of the microhardness but also an inhomogeneous microstructure which is responsible for the difference in hardness behavior between the near surface and the center of deformed wire.

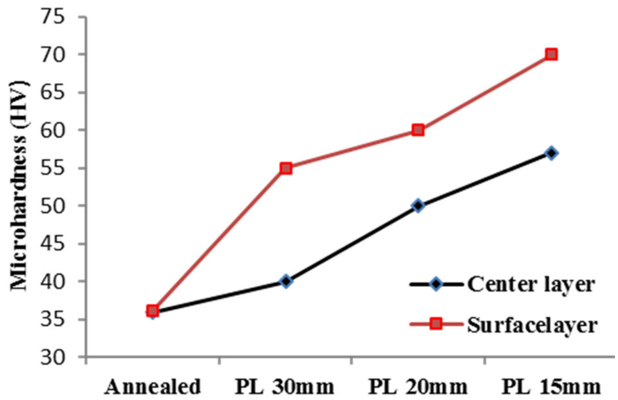

Fig. 8. Microhardness in near surface and center of the torsion deformed wires with increasing number of revolutions

Fig. 9 is a comparison between the hardness of PL 30 mm sample and WD sample. It can be seen that after one pass of wire drawing process, the hardness in wire surface increases to 55 Hv which is very close to the hardness of PL 30 mm sample. But in center of wire, the hardness of drawn sample is higher than the PL 30 mm sample. It may be as a result of accumulating more strain in center of drawn wire compare to the five round twisted sample.

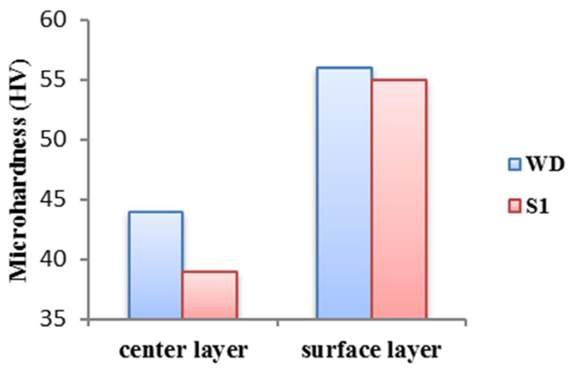

Fig. 9. Microhardness in the surface and center of PL 30 mm sample and WD sample

The hardening after torsion deformation is likely attributed to the reduction of dislocation mean free path with the lamellar dislocation substructures. These substructures can act as obstacles to dislocation gliding and because of high density obstacles in near surface zone, hardening mainly happens in this area more than the center of wire.

3.3. Microstructure

Fig. 10 shows the microstructure images of different samples with different PL of torsional revolutions. According

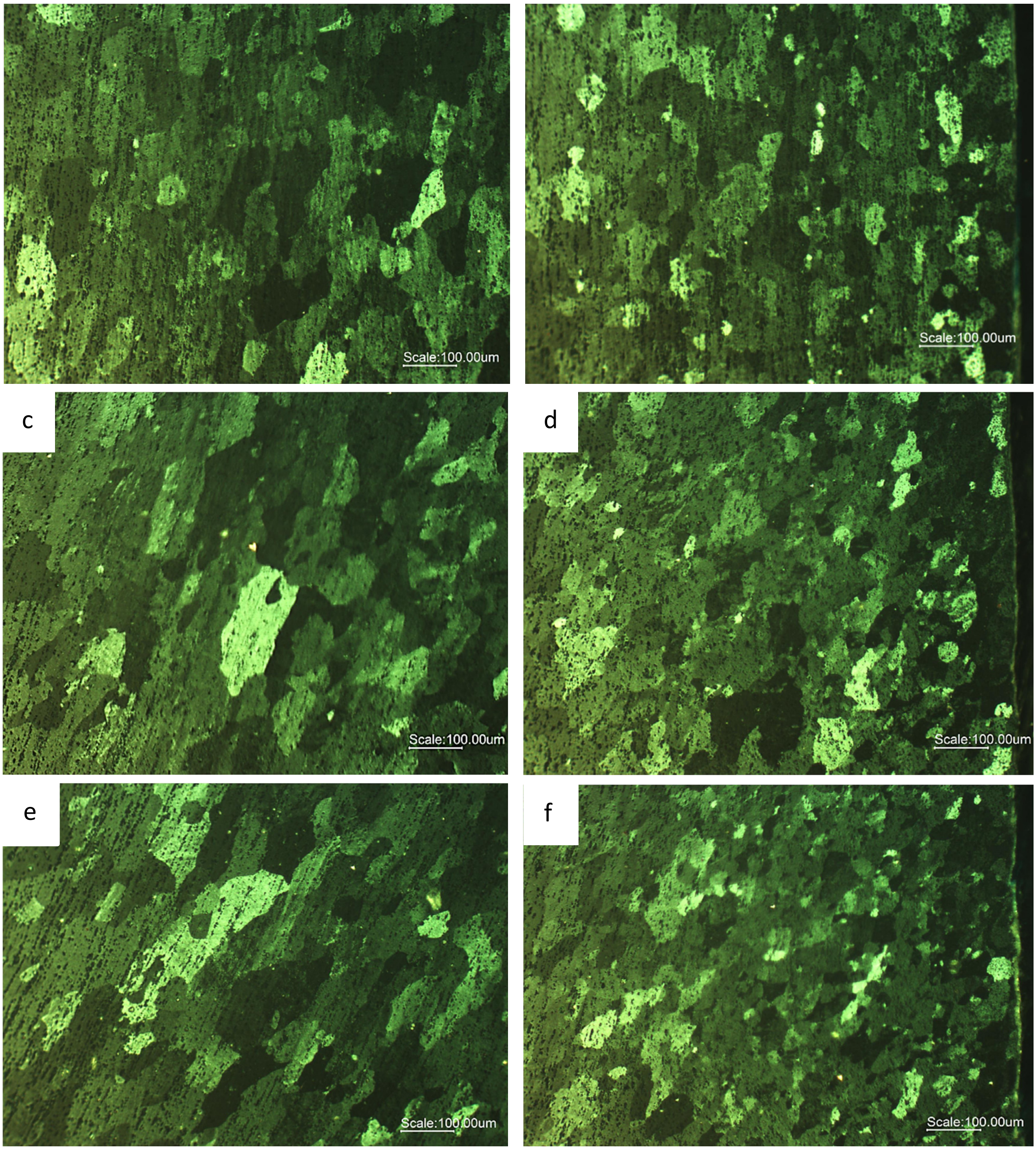

Fig. 10. Microstructure pictures of pre-torsion deformed samples, a) center layer of PL 30 mm, b) surface layer of PL 30 mm, c) center layer of PL 20 mm, d) surface layer of PL 20 mm, e) center layer of PL 15 mm, f) surface layer of PL 15 mm

to these images there is a clear difference between the grain size in the center and surface of processed samples. The grains near the surface are smaller than the grains in center for all samples. In fact, at surface because of higher level of torsional shear strain, grains are smaller. By increasing the number of torsional revolutions, the size of grains of near the surface will decrease strongly.

As Fig. 1 shows, the grain size near center and surface of annealed sample is very similar to each other. Also grains in center and surface do not have a specific direction. By applying torsion deformation, the grain size near the surface is decreased but in the center layer there is not any significant change in grain size as shown in Fig. 10a,c,e. It can be seen that after pre-torsion deformation a spatial gradient microstructure is formed. The grain size decreases continuously from center to surface layer. Also direction of grains is changed according to angle of painted lines after torsion deformation. Fig. 11 shows the measurement angle of the elongated grains from the longitude axis of wire in the center layer. Table 3 presents a comparison between the measurements and calculated angle according to PL and diameter of each sample.

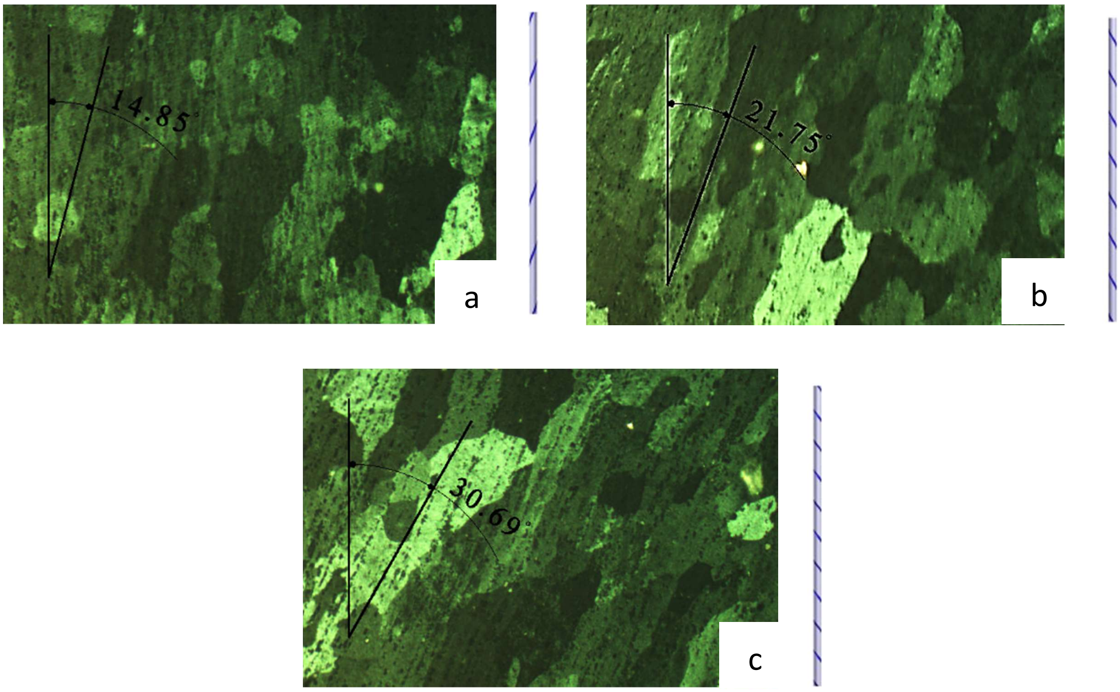

Fig. 11. Angle of elongated grains in center layer, a) PL 30 mm, b) PL 20 mm and c) PL 15 mm

TABLE 3

Measured angles by microstructure images and calculated angles

Sample	Measured angle	Calculated angle
PL 30 mm	14.58	14
PL 20 mm	21.75	21
PL 15 mm	30.69	28

Results show that the grains were elongated according to direction of applied shear strain at the center and surface layer of deformed wire. Fig. 12 shows the shape of elements before and after pre-torsion deformation at the center and surface layer of samples obtained from FE results. It can be seen that the near surface elements are elongated according to the direction of induced shear strain by Torsion. The changing in the initial shape of elements at the wire surface is much higher than the elements at the wire center corresponding to much higher level of equivalent plastic strain at the surface layer.

Table 4 shows the average grain size in the center and near surface layer. According to grain size measurements, grain size in the center layer for PL 15 mm sample decreases to 106 μm from 150 μm for the annealed sample. But the reduction of grain size significantly occurs in surface layer. The average grain size in near surface layer is about 47 μm, while the average grain size in near surface layer of annealed sample was about 120 μm which shows 60% reduction.

TABLE 4

Average grain size in center and near surface layer of different samples

Sample	Center layer average grain size [μm]	Near surface layer average grain size [μm]
annealed	150	120
PL 30 mm	130	100
PL 20 mm	120	60
PL 15 mm	106	47

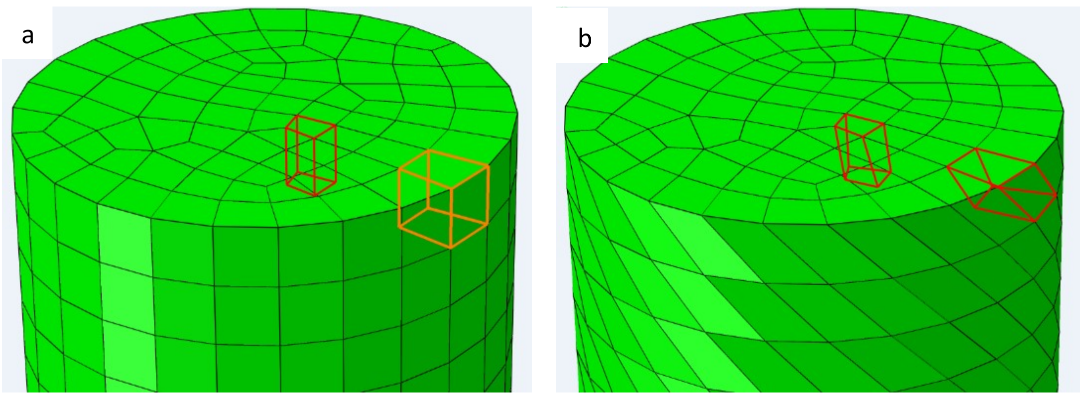

Fig. 12. Grains in center and surface layer, a) before pre-torsion and b) after pre-torsion deformation

4. Discussions

Based on the Results, by increasing number of torsional revolutions, the tensile yield strength and ultimate strength of annealed wires will greatly increase. The significant increase in tensile yield strength is likely due to gradient lamellar dislocation substructures. Also pre-torsion deformation causes gradient microstructures that have smaller grains in near surface layer and much bigger grains in center layer of the specimens. These gradient microstructure causes different mechanical properties such as variant microhardness in the center and near surface layer of pre-torsion deformed samples.

In most papers correlating the evolution of pure AL microstructure, effective strain of 4 is mentioned to achieve ultrafine grains with the grain size of less than 1 µm [18-20]. According to equation 1 and 2, for achieving the effective strain of 4 with pre-torsion deformation, the 150 mm length of wire should be twisted for 82 rounds which would be impossible because of destructive cracks that will appear on the surface of wire in high number of torsional revolutions. These cracks cause early failure of the wire in tensile test. According to stress-strain curves, by applying 10 round torsional revolutions, the ultimate strength of annealed wire increases from 105 MPa to about 150 MPa. However, the elongation of these wires reduces from 22% for annealed sample to less than 3% which might be not suitable for producing cables. Such reduction is unusual for these amounts of the applied strains. Fig. 13 shows the surface of PL 30 mm sample with more magnification.

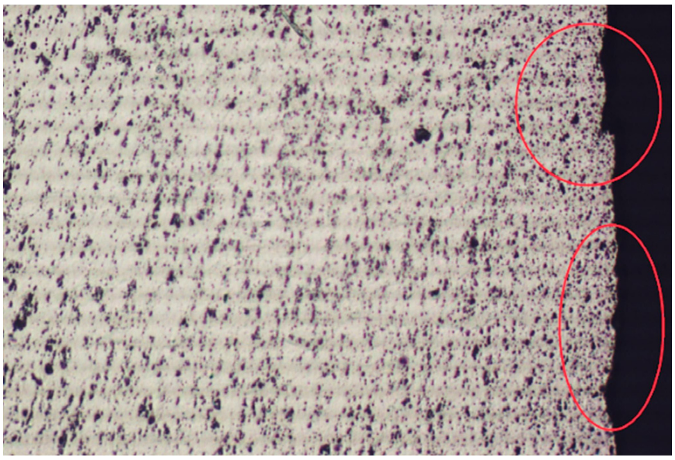

Fig. 13. Wrinkles at the surface of PL 30 mm sample

It can be seen that after applying pre-torsion deformation, according to PL of each sample, some wrinkles would appear at the surface. These defects cause early failure in tensile tests. Consequently, the elongation of pre-torsion samples reduces significantly. Instead, the hardness of these wires is very sensitive to torsion deformation, especially in surface of wire. The hardness of annealed sample increases from 36 Hv to 70 Hv for PL 15 mm sample. Additionally, the hardness of near center areas increases to 57 Hv for this sample. Thus pre-torsional deformation method has obvious advantages as no limitations on material dimensions. Also high efficient, low cost, easy preparation should be noted too. More importantly pre-torsion could be developed for strengthening Al wires that have main usage in electric power transition industry.

5. Conclusions

In this paper, the effect of pre-torsion deformation on the microstructure evolution and mechanical properties of annealed Al wires was studied. The results can be summarized as follow:

(1) The results show that the mechanical properties of pure Al wires are very sensitive to the amount of induced plastic shear strain by torsion. The elongation of the wires decreased strongly (from 30% to about) due to accumulation of dislocation densities and micro size wrinkles at the wire surface.
(2) that by a small amount of plastic shear strain by torsion (about 0.2), the
(3) The results of tensile tests show that by increasing the number of torsional revolution for a certain length of Al wire, The yield strength and ultimate tensile strength increases significantly.
(4) By applying torsion deformation, the grain size in the center of deformed wires decreased, but the main refinement was happened at the near surface areas.
(5) Torsion deformation results an inhomogeneous microstructure causing differences in microhardness between the surface and center of processed Al wires.

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