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Effect of Heat Treatment on Microstructure and Mechanical Properties of Medium Carbon Steel Drawn Wire.

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Abstract. In this article, the effect of heat treatment on the microstructure and mechanical behavior of medium carbon steel wire intended for the spring mattress is investigated using scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), X-ray diffraction, Vickers hardness (Hv), and tensile strength. The results indicate that the microstructure elongation along the wire axis is observed with the bending and kinking lamellae at the deformation level of 57.81%, this change appears as a fracture in the microstructure and leads to an increase in hardness, tensile strength, and intensities of diffraction patterns. After heat treatment, we observed a redistribution in the grain, which is almost the same in the wire rod and drawn wires; indeed, this led to a decrease in hardness, tensile strength, and augmentation in intensities of peaks. The EBSD pole figures reveal the development of texture in the cementite slip plane (001).

Introduction

Wire drawing process is one of the most used metal forming processes within the industrial field [1]. Cold drawn pearlitic wire has a great practical importance in structural applications, like suspension cables, tire cord and springs, where high strength is required, together with acceptable level of toughness [2]. Cold drawing produces changes in the pearlite colony (first microstructural unit) in the form of increasing slenderising and progressive orientation parallel to the wire axis [3,4]. There are many investigators who have studied cold-drawn pearlitic steels; and based on the important classical work performed, Embury and Fisher (1966) [5] investigated the evolution of the microstructure and crystallographic texture of a pearlitic steel wires (0.93% C) during wire drawing process and they described the development of the fibrous structure (morphological texture) and a crystallographic texture of fiber $\langle 110 \rangle // WDD$ (where WDD is the wire drawing direction parallel to the wire axis (WA)). From the newest studies, Pankaj Kumar et al. (2011) [6] investigated the microstructure and texture during wire drawing of pearlitic steel (0.8% C); they found wire drawing induces elongation of ferrite grains with the development of $\langle 110 \rangle$, Jesús Toribio et al. (2014) [7] studied the relationship between the microstructural changes caused by the cold drawing process in pearlitic steel wires (0.7% C); they found that cold drawing produces microstructural orientation in pearlitic steel, so that pearlitic lamellae progressively orientate in the drawing (axial) direction. While its interlamellar spacing decreases during straining and at the

mechanical level this produces an improvement of mechanical properties such as the yield strength and ultimate tensile stress. M.C. Nebbar and M. Zidani et al (2019) [8] studied the evolution in the microstructure, texture and mechanical properties of medium carbon steel wires obtained by wire drawing (0,68% C); they found before wire drawing the pearlite colonies are distributed in an irregular way, and after wire drawing the pearlitic colonies and the cementite lamellae present in the microstructure drawn wire at 43% which are the bended, kinked, thinned and aligned cementite lamellae along wire axis, these results according with Pankaj Kumar [6].

It is known that cold-drawn pearlitic wires are unstable and sensitive to heat treatment [9]. However, annealing treatment changed cementite structure from disordered to nanocrystalline state, and the recrystallized cementite impeded dislocation motion and broke up around high-density dislocation zones, resulting in micro-cracks during torsion tests. [10]. The degradation of lamellar pearlites during annealing is accompanied by cementite dissolution due to the diffusion of carbon atoms, cementite lamellae could assume a spherical shape when heated up to 400 °C. [11,12]. The continuous evolution of carbon from its crystalline cementite phase into its elemental form during wire drawing and its re-segregation into spheroidal cementite during subsequent heat treatment is reflected in its changing fracture behavior. Although the high temperature annealing results in significant improvement in damage tolerance, accompanied by large-scale plasticity, although associated with a drastic reduction in strength. [13]

In the present work, we focused on studying the effect of heat treatment at 950°C for 5 min on the evolution of microstructure and mechanical properties of medium carbon steel wires (C68D) (used for the spring mattress, Bonnell springs). In this study, we used, electron microscopy (SEM), electron backscatter diffraction- (EBSD) and X-ray diffraction, Vickers hardness (hv) and the tensile strength.

1. Studied material

The studied material is a medium-carbon steel C68D whose chemical composition is presented in table 1. This commercial steel is intended for the manufacturing of spring mattresses.

Table 1. Chemical composition of studied material C68D (wt%).

Composition	C	Mn	Si	Cu	Cr	Ni	Mo	S	P	Al
wt%	0.655-	0.649-	0.18-	0.048-	0.051-	0.036-	0.012	0.008	0.007	0.002
	0.675	0.650	0.201	0.145	0.100	0.083				

The material is presented as a wire rod ($\varnothing=5.5$ mm) and two drawn wires corresponding respectively to two different true strains ($\epsilon_1= 43.63\%$, $\epsilon_2= 57.81\%$).

The true strain is calculated by equation (1):

$$\epsilon = [(S_i - S_f)/S_i] \times 100 \% \quad (1)$$

S_i and S_f designate the initial and the final sections of the wire, respectively.

The samples were annealed at temperature 950°C (1223 K) for 5 minutes without controlled atmosphere and cooled slowly, inside the furnace to room temperature.

The microstructure was analyzed by a scanning electron microscopy (SEM), and electron backscatter diffraction (EBSD). In order to study the variation in crystal structure, X-ray diffractograms

were used. And to follow the evolution of the mechanical properties of the wires, the Vickers microhardness (Hv) and the tensile test were applied.

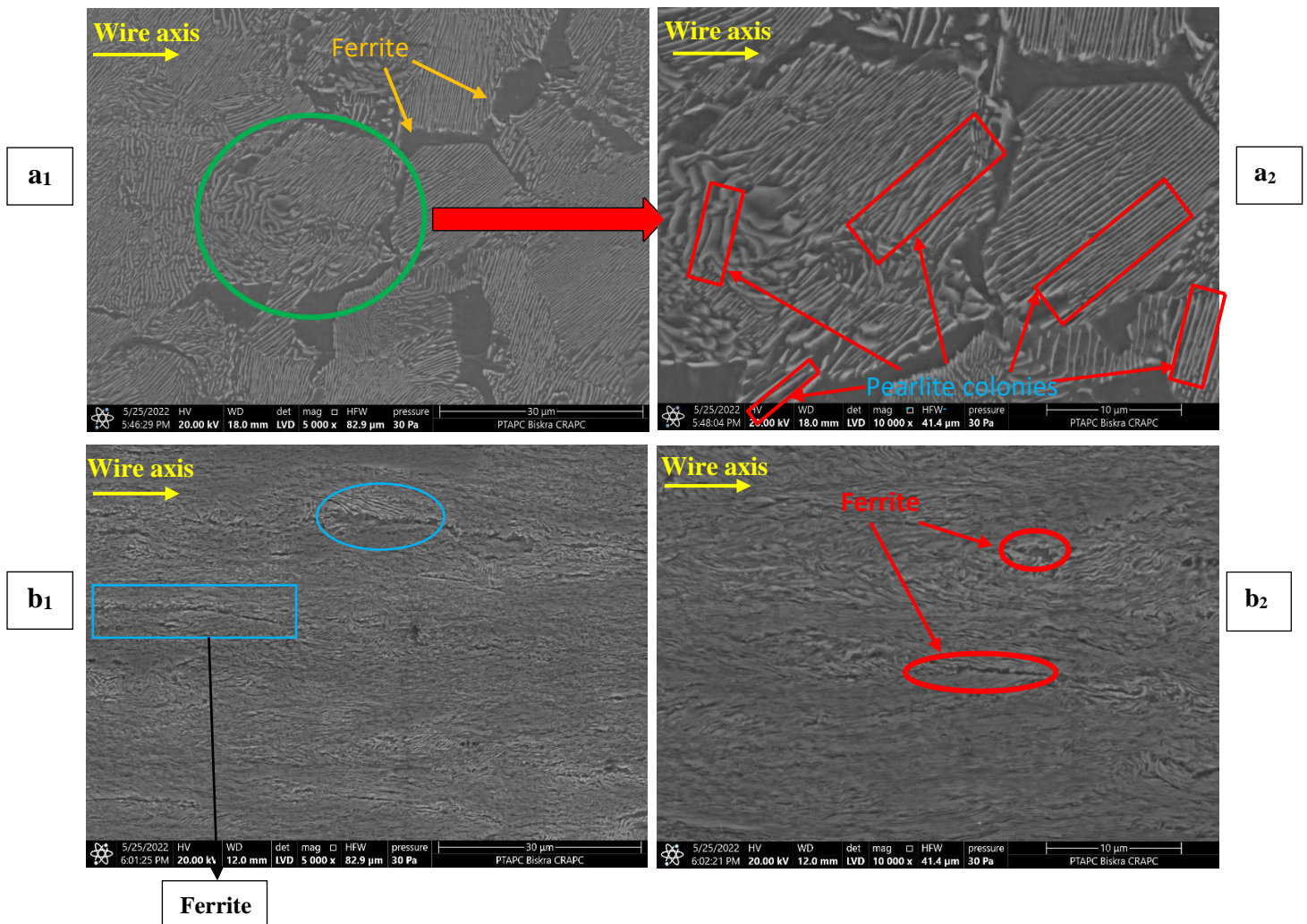
2. Results and Discussion:

3.1 Drawn state

3.1.1 Microstructure

The Figure 1 shows the microstructure of a longitudinal section of the wire rod and drawn wires ($\epsilon_1=43.63\%$, $\epsilon_2= 57.81\%$) before annealing. The microstructure of the rod wire material showed a pearlitic-ferritic structure, with a large grain and an irregular distribution of the colonies of pearlite.

At the drawn state level, we noticed a certain difference in the evolution of the microstructure between our samples and the samples studied by Nebbar et al. [8] of the same steel. In our batch, we only observed two types of cementite lamellae: Kinking lamellae and Bending lamellae (marked with a yellow rectangle and circle in Fig. 1 c₂) at 57.81 % strain. While Nebbar et al. [8] observed four types of cementite lamellae (the bended, kinked, thinned and aligned cementite lamellae along wire axis) at 43.6 % strain on their batch. This effect is attributed to the chemical composition which was slightly different between these two batches. In their batch, the difference was remarkable on the following additives: + 0.097 Cu, +0.049 Cr, +0.047 Ni. According to Ribeiro Duarte et al. [14], this morphology of the pearlitic colonies "aligned with drawing direction" is due to the curling structure which was observed on the cross section of the drawing wires (0.7 wt% C, 0.489 Mn, 0.225 Si, $\epsilon=2.52$).



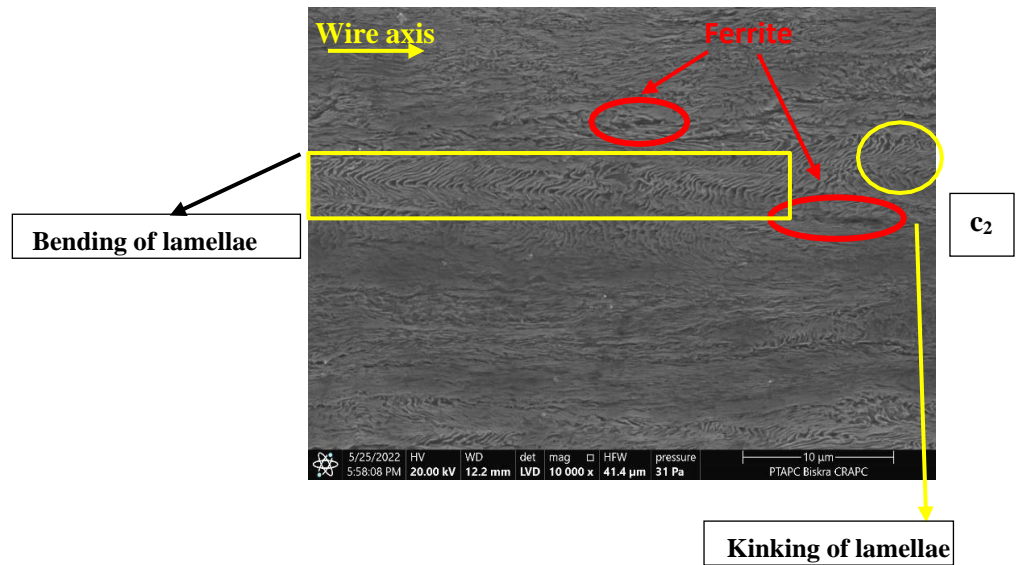


Fig. 1. Scanning electron micrographs for the wire drawing: (a) wire rod and (b) deformed wires $\epsilon_1=43.63\%$, (c) deformed wires $\epsilon_2=57.81\%$. (a_1 , b_1 , for average grain size $30\mu\text{m}$; a_2 , b_2 , c_2 , for average grain size $10\mu\text{m}$).

2.2 Annealed state

The three wires were annealed at 950°C (1223K) for 5 min.

3.2.1 Microstructure

As we can see in Fig. 2 a, the cementite lamellae of the wire rod adopted a curved shape with no preferred direction (marked with a red circle). Nevertheless, this curved feature was observed by Toribio [15] in heavily cold-drawn pearlitic steels after six drawing steps (transversal section). He related this phenomenon to the big difference in hardness between the two phases pearlite (hardest and brittle) and ferrite (softer and ductile) (well observation in average grain size $10\mu\text{m}$, in Figure. 2 a2).

After annealing, we notice a very light diminutive decrease in the grain size with increase in the strain level depicted in Fig. 3 c. On the drawn and annealed wires, we notice a clear reduction in the interlamellar space of the pearlite, compared to the annealed wire rod. In the wire ($\epsilon_1=43.63\%$) we observed the formation of a so-called quasi-spherical cementite, in certain places of the grain boundaries (Fig. 2 b) (marked with a yellow circle). According to F.Fang et al, during the annealing of cold drawn wires, carbon atoms re-settle at ferrite/cementite interfaces. The tensile strength of the wires decreases and the elongation increases (in section 3.4). With a further increase in the hold time, the spheroidization of lamellar cementite occurs, driven by the minimization of surface energy for lamellar cementite. [12]. On wire ($\epsilon_2 =57.81\%$) (Fig. 2 c), we observed a more decrease in the size of the ferritic grains and the formation of small fragmented lamellae of cementite uniformly oriented and combined over several micrometers.

3.2.2 Textures

We recall that the work carried out by Nebbar et al. [8], on this steel, revealed the development of the $\langle 110 \rangle$ fiber after drawing. And as we can see, after annealing, the texture of the wires has completely changed (Fig.3 a). The pole figures show an increase in the intensity of the $\langle 001 \rangle$ fiber according to the increasing deformation compared to the $\langle 111 \rangle$ and $\langle 110 \rangle$ fibers (Fig. 3 b). According to Gil Sevilano [16], the $\langle 001 \rangle$ fiber is one of the directions appurtenant to the planes (001) which are considered as cementite slip planes. It's the necessary condition for a crystal to behave ductility; i.e., to possess five independent slip systems, would be unfulfilled if the (001) and (010) were the only available slip planes. The observation of four possible new slip planes supports the potential ductility of cementite in the drawn wire [16]. These changes in microstructure features

and textural were produced by dissolved cementite during annealing. This is consistent with what we have previously reported about fragmentation of cementite lamellae in wire ($\epsilon_2 = 57.81\%$) microstructure (Fig. 2, c), and the development of the $\langle 001 \rangle$ fiber.

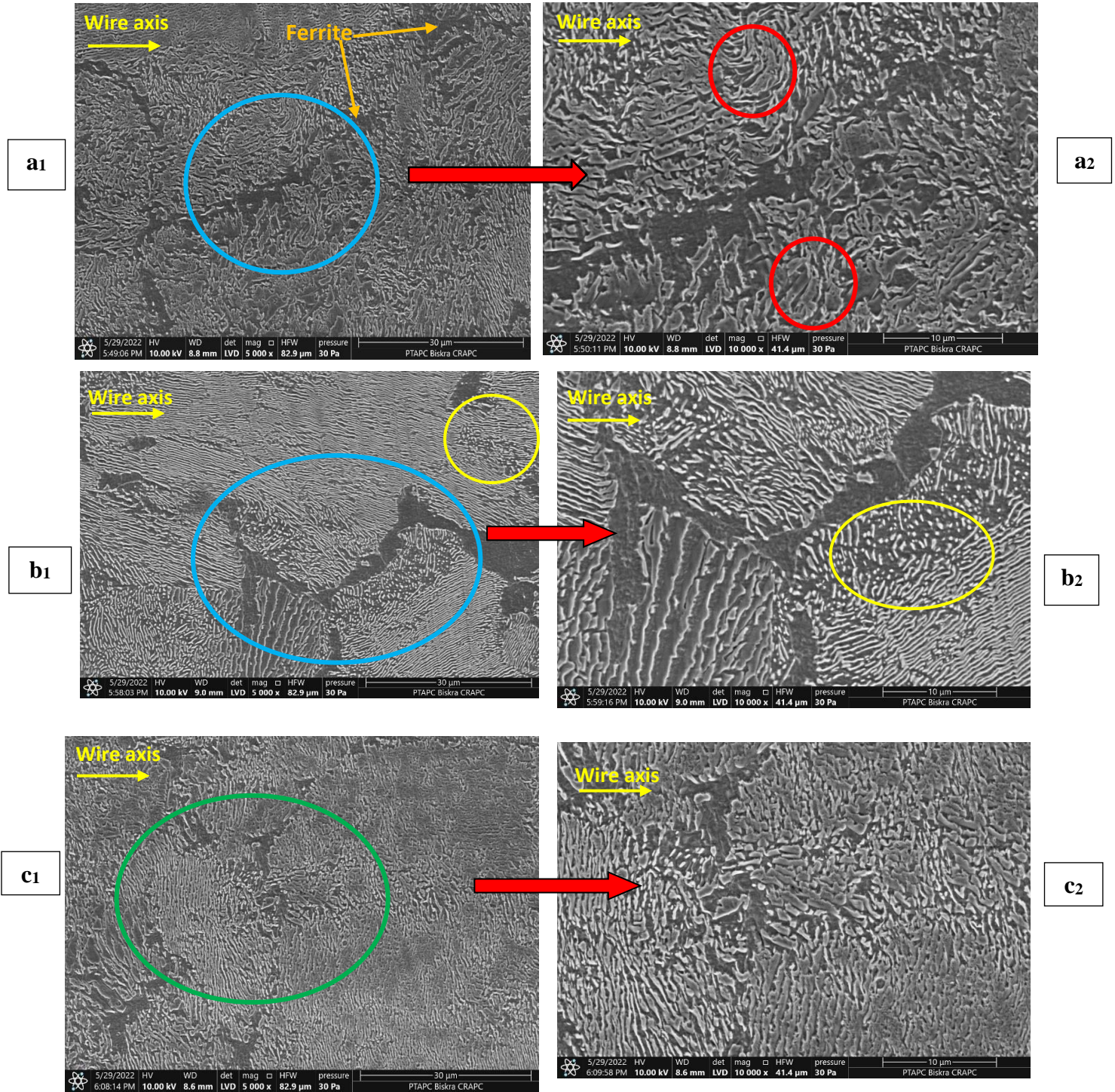


Fig. 2. Scanning electron micrographs for the wire drawing (wire rod and deformed wires) after annealing at 950°C for 5min, (a) wire rod and (b) deformed wires $\epsilon_1=43.63\%$, (c) deformed wires $\epsilon_2=57.81\%$. (a₁, b₁, c₁, for average grain size 30 μm ; a₂, b₂, c₂, for average grain size 10 μm).

Wire rod

$\epsilon_1=43.63\%$

$\epsilon_2=57.81\%$

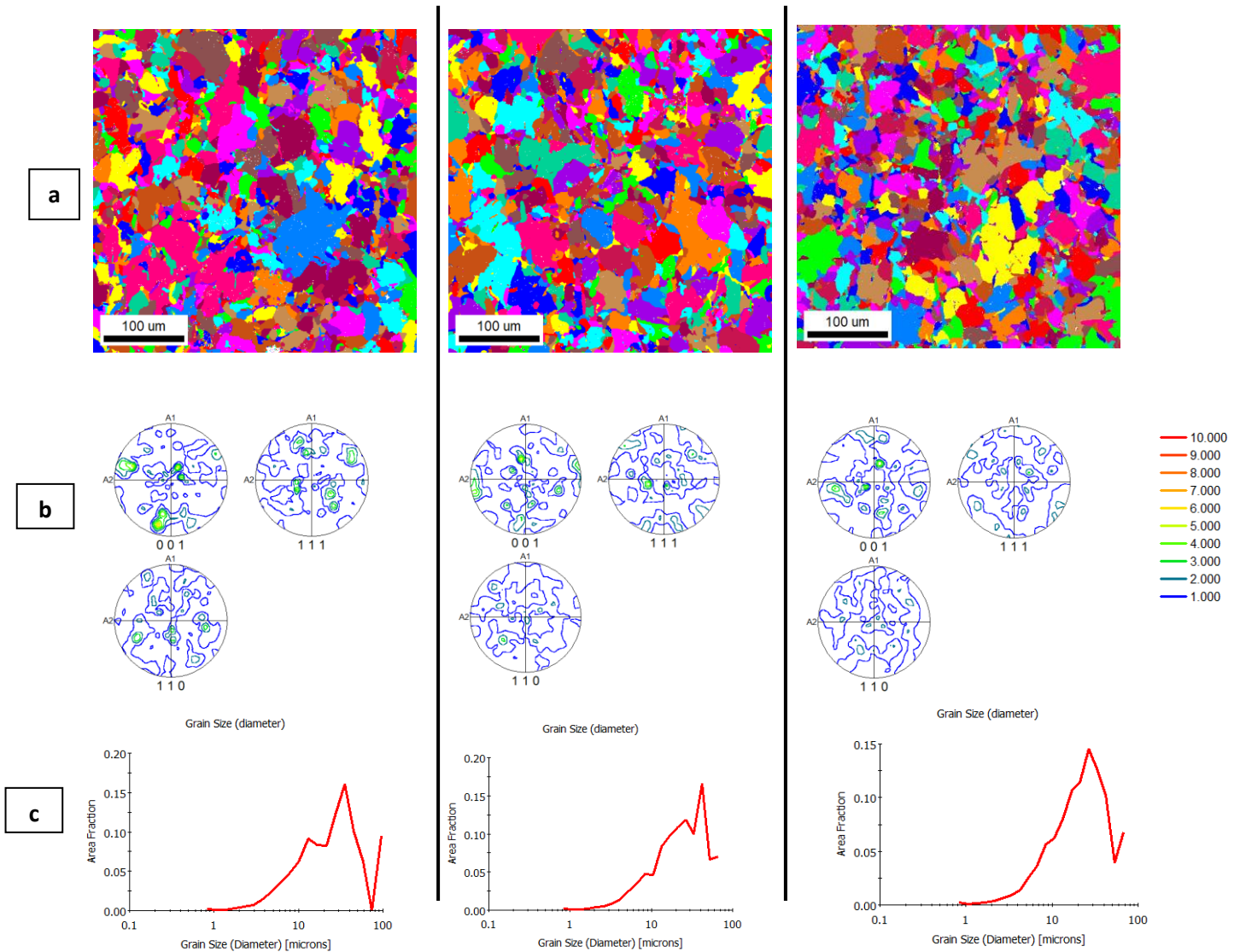


Fig. 3. a) EBSD maps, b) Major axis inverse pole figure, c) grain size, of the cold drawing annealing pearlitic steel wires (C68D-2) at different strain levels.

3.3 X-ray diffraction

Figure. 4 a, present the results of X-ray diffractograms for drawn- wire steel C68D-2 at different deformation levels ($\epsilon_1=43.63\%$, $\epsilon_2=57.81\%$). As can be seen, the intensities of peaks (110), (200) and (211) increase with increasing strain. However, Nebbar et al. [8] reported a decrease in the peak's intensities when the deformation increase. This change is attributed essentially to the chemical composition which was slightly different between these two specimens.

Figure. 4 b, presents the XRD results after annealing, the first noted was no significant peak displacement, and the increase in the all-peaks intensities. According to Ning [17] if the dissolution of the cementite is caused by the binding mechanism of carbon atoms and dislocations, the excess carbon atoms would locate around the dislocation, which cannot cause the displacement of the ferrite diffraction peaks [17].

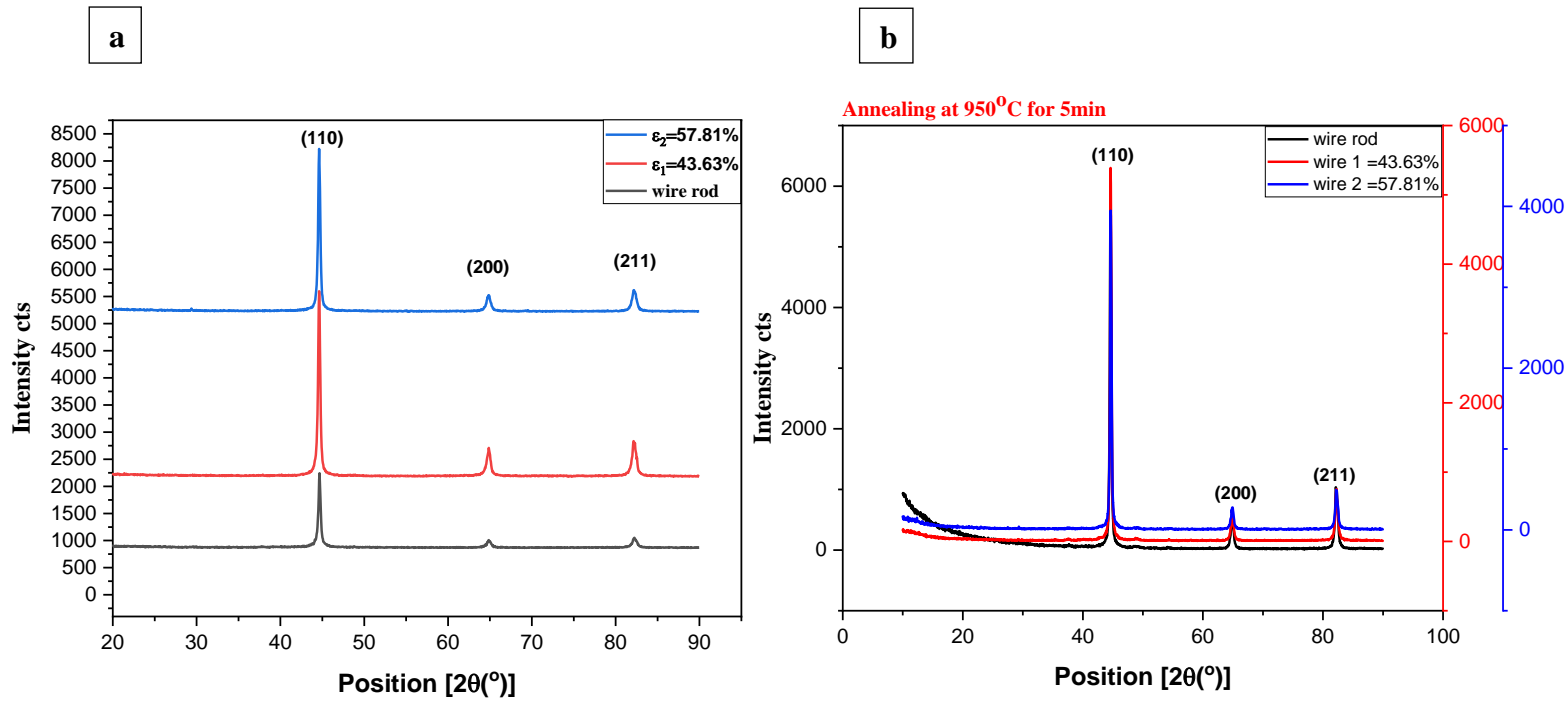


Fig. 4. X- ray diffractograms of the drawing steel wires C68D-2 with different deformation levels (a) before and (b) after annealing.

3.4 Mechanical Properties

The Figure. 5 indicates the hardness and tensile strength as function of drawing strain before and after annealing. Before annealing the hardness and tensile strength of the medium steel drawn wire increases gradually with increasing the deformation level. This can be attributed to the decreasing of the interlamellar spacing during wire drawing of the steel according to Kumar et al. [6]. A similar result has been reported by Kisrane et al. [18], on the case of steel (0.89% C, 0.63% Mn, 0.31% Cr, 0.32% Si, 0.011% Cu), and Nebber et al. [8] in steel C68D-2 with different chemical compositions whereas in our samples the hardness value of is higher.

After heat treatment, as can be seen in Fig. 5 a, the hardness and the tensile strength decreases considerably compared to drawn wires (before annealing) but they were almost the same in annealed wires, the hardness influenced by dissolved cementite because the cementite in slip planes (001) would be brittle according to Sevilano [16].The loss in strength was attributed to grain coarsening and spherodized carbide formation at the grain boundaries and triple junctions, while the loss in both strength and ductility will eventually dictate whether the fracture is brittle or ductile. [13]

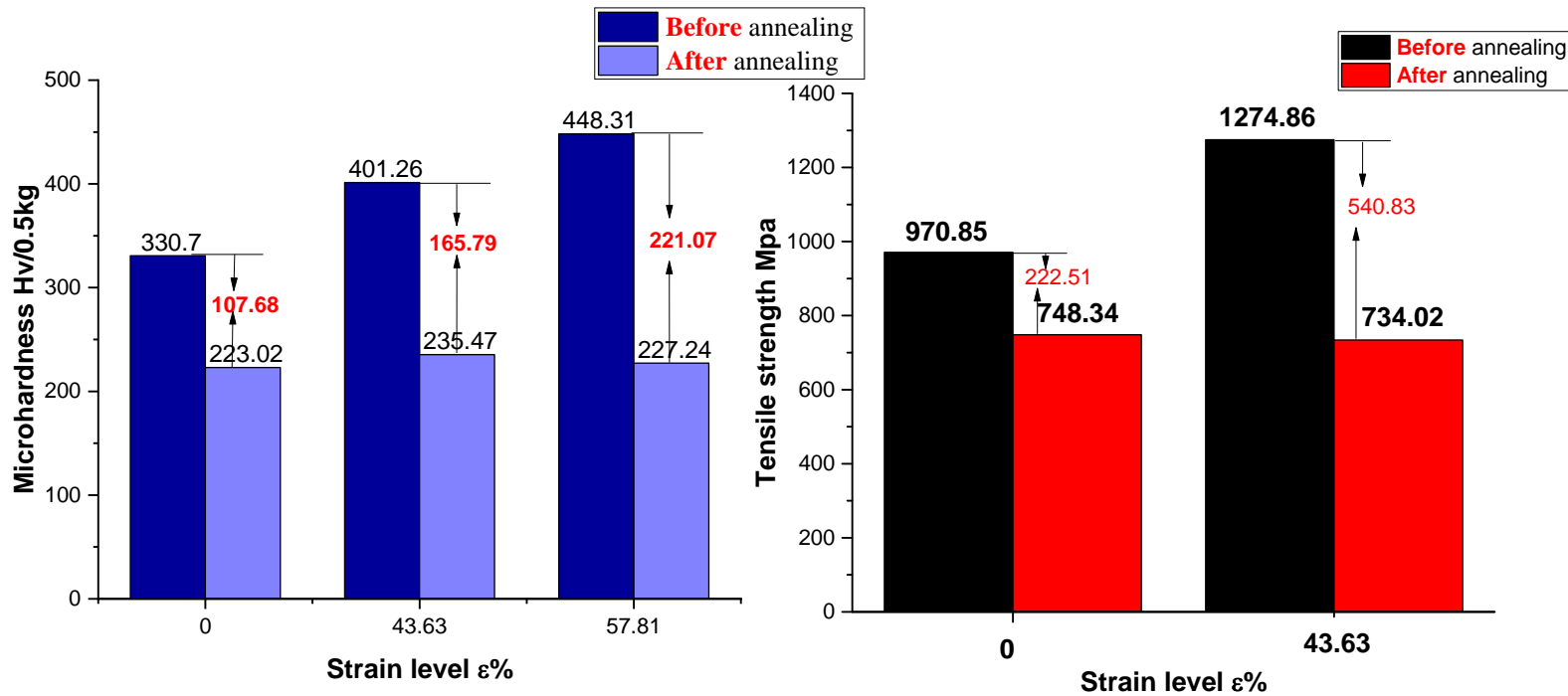
a**b**

Fig. 5. a) Microhardness evolution, b) tensile strength, of the drawing steel wires, before and after annealing.

3. Conclusion

According to all that has been developed previously, we can deduce the following results:

- Annealing at 950 C° for 5 min, leads a very light diminutive decrease in grain size, reduction in the interlamellar space of the pearlite and the formation of so-called quasi-spherical cementite in the strain level of $\epsilon_1=43.63\%$. Fragmentation in cementite lamellae in microstructure at the deformation level of $\epsilon_2=57.81\%$ and the curved lamellae in wire rod.

- The annealed drawn wires exhibited an increasing in intensities of peaks of diffraction patterns compared to drawn and rod wires and no significant peak displacement due to dissolved cementite.

- Although the time of annealing was brief (5 min), the hardness and tensile strength decrease in wire rod and drawn wires due to the dissolved cementite (there was a new microstructure).

- A change in texture in all the wires and appearance of new texture, where the most intensity is in the slip plane (001).

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