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Microstructural Evolution of a Pearlitic Steel Subjected to Thermomechanical Processing

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The microstructural alterations suffered during the process of drawing deformation and subsequent annealing of pearlitic steel wires, were evaluated by scanning electron microscopy and atomic force microscopy. The deformed material showed the curling structure in cross section while, in the longitudinal section, the lamellae was aligned with the drawing direction. The microstructural characterization of deformed samples also allowed observing an interlamellar spacing reduction and the intermediate lamellae alignment process. After the heat treatment at 1000ºC for 5 min the microstructure was restored, however, few recrystallized grains were observed. The recovery was the dominant phenomenon, due to factors associated with curling structure that inhibited recrystallization.

Keywords: *Microstructural Characterization, Wire drawing, Annealing, SAE 1070 Steel.*

1. Introduction

The combination of high resistance associated with acceptable levels of ductility of the high carbon steels allows their application in various sectors, such as stay cables, piano strings, beads, etc. Therefore, these steels have been, for many years, the topic of considerable scientific research[1]. The structure predominantly pearlitic is responsible for this combination of properties. This staggerd structure of pearlite incorporates ductile constituent (ferrite) and the constituent with high hardness (cementite).

The wire drawing process employs a series of wire dies to reduce the cross-section of the wire and at the end of the process is applied heat treatment to restore mechanical properties. The microstructural evolution during these processes involves several mechanisms directly related to the lamellar structure. Recently, much effort has been made to improve the tensile strength of high carbon steel wires, with a maximum value of 7.0GPa obtained with nanostructure through severe deformation[2,3]. However, many aspects related to the properties of high carbon steel wires are still not clear, such as microstructural changes resulting from drawing, hardening properties typical of pearlitic steels, formation of the curling structure, etc[4].

The objective of the present study was evaluate the microstructural evolution of a SAE1070 steel wire subjected to deformation by drawing and subsequent heat treatment. The annealing above critical temperature was performed in order to evaluate the combined results of restoration phenomena and phase transformation in deformed material. Considering that, the severely deformed pearlite microstructure has peculiarities that interfere not only in the mechanical properties, but also in the restoration processes during the heat treatment. The investigation of these mechanisms is also necessary in austenite phase region once it has not explored enough in the literature.

2. Experimental

SAE1070 steel wires with chemical composition of 0.712C, 0.01S, 0.489Mn, 0.007P, 0.225Si, 0.003Al, 0.016Cr, 0.009Cu, 0.006Ni, 0.005Mo, 0.01N, expressed in wt.%, were used in this study. The as received material with 5.50 mm diameter was produced by hot rolling with continuous cooling. The steel wire was cold drawn in 12 passes with reduction rate of 15 to 20% until the diameter of 1.55 mm. After drawing process, the samples were annealed in a tube furnace at 1000 °C for 5 minutes without atmosphere and cooling rate control. The microstructural characterization was carried out by scanning electron microscopy (SEM) and atomic force microscopy (AFM).

3. Results and Discussion

3.1 As received material

The as received material showed a predominantly pearlitic microstructure with the presence of pro-eutectoid ferrite. These characteristics are compatible with the hot rolling process in which the material was submitted. Figure 1 was

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obtained with the help of EVO MA10 Scanning Electron Microscope - Zeiss, with signal secondary electrons. It is possible to identify small pro-eutectoid ferrite grains among the pearlitic grains. This ferrite grains are marked with a dotted circle. The amount of ferritic grains is reduced due to the fact that the SAE 1070 steel has a carbon concentration close to the eutectoid composition. It is also noted that the colonies in the pearlitic grains, which are composed of alternating lamellae of ferrite and iron carbide have different macroscopic orientations[5].

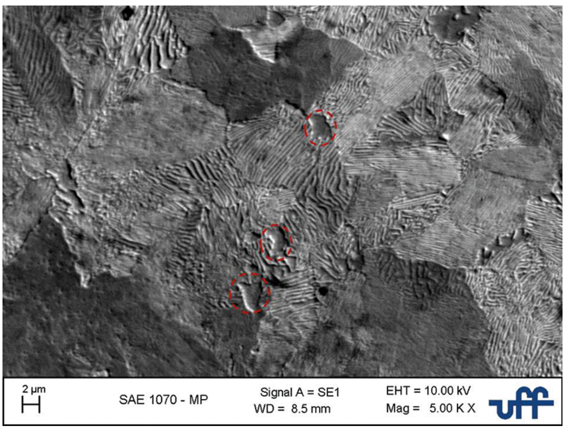

Figure 1. SEM. Cross section of SAE 1070 steel in the initial condition.

3.2 Deformed material

The drawn material was subjected to a high deformation that resulted in morphological changes in its constituents. Figure 2 shows the microstructure of wire drawn steel with deformation of 2.52. It can be seen, in the cross section of the wire, the presence of a structure commonly referred as curling due to the fracture of the cementite lamellae and twisting of the ferrite lamellae[5,6]. This wavy or intercurling microstructure, exhibited by pearlite colonies, is typical in the drawn wires with BCC structure[7]. Fragmentation and dissolution of cementite during deformation results in an interaction between dislocations and carbon atoms[8]. However, Nematollahi[9] said that the cementite lamellae are fragmented into nanoscale particles as a result of the substantial mismatch between the curvatures of the two phases. This mismatch in curvature is explained by the fact that the cementite phase is harder and more resistant than ferrite, which leads to different behaviors during deformation.

The pearlitic structure when deformed does not show the same microstructure characteristics in the longitudinal and cross sections. This anisotropic behavior can be observed in Figure 3.

The cross section shows the curling structure as discussed before, and in the longitudinal section one can see that the lamellae are fully aligned with the drawing direction. Several studies[10,11] show that with gradually increase of the drawing strain, most of pearlite colonies rotate aligning

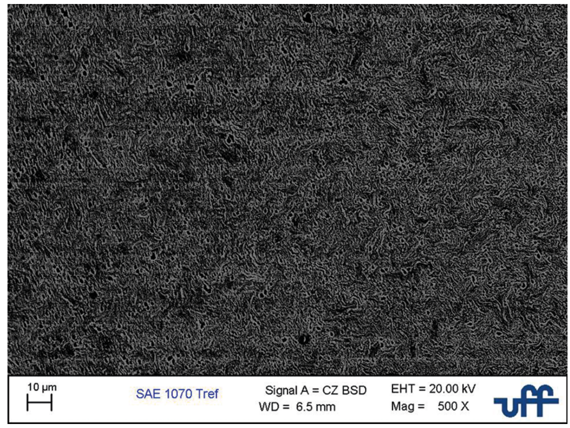

Figure 2. SEM. Cross section of SAE 1070 steel cold-deformed with accumulates strain of 2.52.

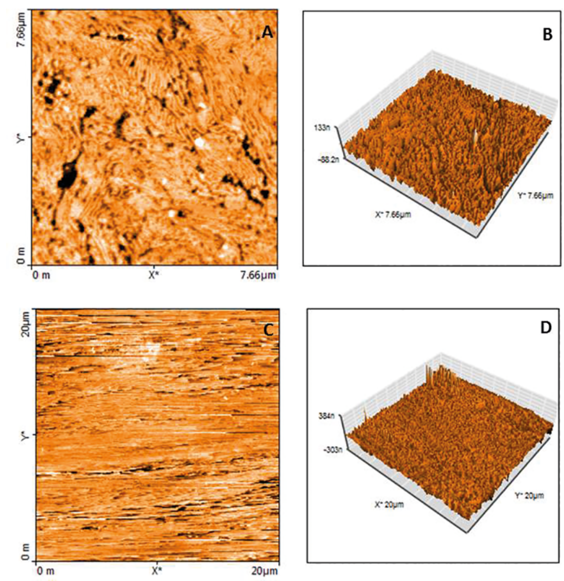

Figure 3. AFM. Micrograph of SAE 1070 steel, cold-deformed with accumulated strain of 2.52 (A) cross section and (C) longitudinal section. Topography of SAE 1070 steel, cold-deformed with accumulated strain of 2.52 (B) cross section, with the analyzed area of 58.6756 µm2 and (D) longitudinal section, with the analyzed area of 400 µm2.

with drawing direction resulting in elongation and further reduction of interlamellar spacing. The longitudinal section is parallel to drawing direction. The apparent contradiction between the structure with twisted and fragmented lamellae shown in cross section, and the elongated lamellae observed in the longitudinal section is attributed to inhomogeneous deformation of pearlite colonies with different spatial orientations[12]. Similar behavior was found in[13] in which a deformation of 2.7 caused the rotation of all the cementite lamellae next to the drawing direction. It is also possible to observe that in both sections, the thickness of the cementite lamellae and the interlamellar spacing decreased dramatically leading to a considerable increase in the interfaces volume fraction. Considering that the ferrite-cementite interfaces act as barriers to the movement of dislocation, may occur, the tendency of orientation of the dislocation structures as shown in some studies[14]. Thus, the increasing of interfaces volume fraction contributes considerably to the hardening of the pearlitic steel, as well as to non-uniform deformation distribution.

The cementite lamellae which, initially had random orientation, have become gradually aligned in the drawing direction as the deformation was increasing. The reorientation degree of cementite lamellae depends on the initial angle between the lamellae and drawing direction, the greater the angle, the greater is the reorientation and the microstructural changes[6]. The lamellae that were favorable oriented or parallel to the drawing direction were plastically deformed and were thinning until form a fibrous structure. At the same time, the lamellae that were oriented in unfavorable positions to drawing direction bended and or twisted[15].

Figure 4 shows the longitudinal section of the deformed material. The image allows to observe the lamellae alignment with drawing direction. However, there are colonies of lamellae that were possibly placed unfavorable to drawing direction. This phenomenon occurs because these lamellae were positioned normal or slightly inclined to the drawing direction. During wire drawing, a process of bending and twisting of the lamellae started until them align to drawing direction. The lamellae located in the central region of the image, marked with a dotted rectangle, are examples of this transition process.

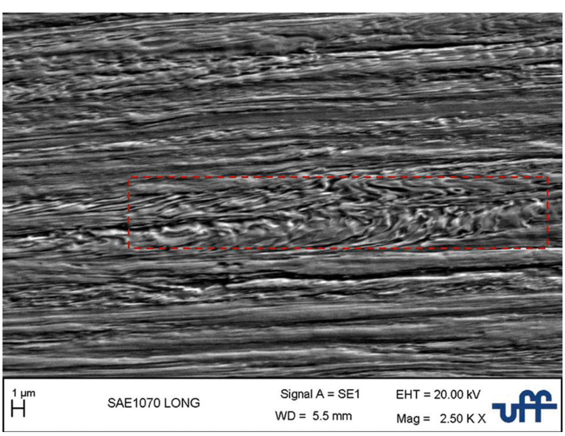

Figure 4. SEM. Longitudinal section of SAE 1070 steel cold-deformed with accumulated strain of 2.52.

Similar structures were identified in Kumar[15] and Tagashira[16] studies that submitted a pearlitic steel to wire drawing and rolling. The rolled material also presented the formation of coarse lamellae with shear bands. This structure was not identified in the present work. It is important to notice that, these lamellae in the intermediate process of alignment with drawing direction, only have been identified in the central region of the sample, while in regions near the wire surface, only aligned and thin lamellae were observed. This occurs due to non-uniform strain distribution during drawing, where the core of the wire undergoes a less severe deformation compared to regions near the surface, soon, the degree of inclination is also smaller.

3.3 Annealing material

After plastic deformation experienced during wire drawing, the mechanical properties of the material are unsuitable for other reduction passes because the reduced ductility and high strength. Therefore, to obtain a further reduced diameter wire, an intermediate heat treatment is required in order to reestablish the properties and characteristics of the deformed material. Figure 5 shows the microstructure of SAE 1070 steel annealed during 5 min. It is possible observe that curling structure, consisting of fragmented and twisted lamellae, is no longer present. This indicates that phase transformation and recovery phenomena acting during annealing were able to significantly change the microstructure during heat treatment, even with a short-duration annealing. The image allows observe the new grains as a result of recrystallization phenomenon. It is also noted a reduction of interlamellar spacing compared to the as received microstructure. However, no preferential orientation of lamellae colonies is observed even after uniaxial deformation.

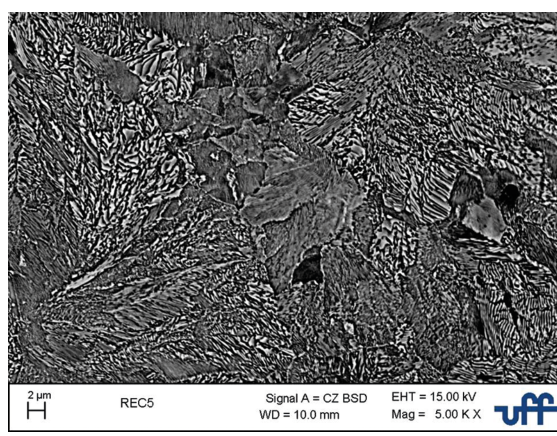

Figure 5. SEM. Cross section of SAE 1070 steel annealed at 1000ºC for 5 min.

According to Storojeva[17], when a pearlitic steel subjected to high strain rate, is annealed, the recovery phenomenon becomes dominant and consumes most of the energy stored as defects. Therefore, reducing the potential for nucleation and growth of new grains. Several factors can be attributed to the inhibition of recrystallization, however all of them are directly related to strain rate. The curling structure is associated with the formation of <110> texture during drawing[7], this intense texture of the fibers reduces the driving force for recrystallization and decreases the mobility of grain boundaries by the formation of low angle grain boundaries[18,19]. In addition, during drawing occurs the fragmentation of cementite lamellae, forming small particles dispersed in the microstructure. These particles create a high drag force for the migration of high angle boundaries[17]. Another factor to be considered is presented by Li[20]. According to this study the carbon segregation at grain and subgrain boundaries reduces the energy, thus hindering the migration of these boundaries.

It is known that the recovery of deformed materials begins quickly with dislocation rearrangement to form more energetically favorable configuration[17], furthermore, at the beginning of annealing at temperatures near 200 ° C, only recovery is observed in the material[20]. Thus, it can be concluded that, as the various factors mentioned above that inhibit recrystallization, recovery will consume most of the stored energy.

The way recovery process occurs is still not clear[21], however it is known that it promotes elimination of defects, especially the rearrangement and annihilation of dislocations. Zhang[6] reported that the dislocation density in ferrite lamellae increase of 7.5 x 10^{13} m^{-2} to 2 x 10^{16} m^{-2} after wire drawing process with 3.68 accumulated strain. This concentration decreases drastically when the deformed material is subjected to a heat treatment. Recently, the dislocation density in an annealed pearlitic steel manufactured by cold drawing with deformation of 3.0 was measured. It was reported that dislocation density decreases to 8.53 x 10^{14} m^{-2} after annealing at 450 ° C for 30 min[20].

4. Conclusions

The curling structure, was observed in cross section while in the longitudinal section the most lamellae were aligned with drawing direction. However, some lamellae were also identified in intermediate alignment with drawing direction, proving the heterogeneity deformation along thickness of the wire. The deformed material also showed a reduction of interlamellar spacing resulting in interfaces volume fraction increase. After annealing, was observed that recovery was the dominant phenomenon. Such behavior is caused by factors associated with the curling structure, which act as inhibitors of recrystallization.

5. Acknowledgements

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