Original Article

Effect of electropulsing on microstructure and hardness of cold-rolled low carbon steel

Reza Alaghmand Fard, Mohsen Kazeminezhad*
Department of Materials Science and Engineering, Sharif University of Technology, Azadi Avenue, Tehran, Iran

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A B S T R A C T
The application of electropulsing treatment (EPT) is studied on the microstructure and hardness of cold-rolled low carbon steel. The effects of electrical pulses on the grain refinement, precipitate size evolution and hardness are investigated. It is found that applying electrical pulse decreases the grain and precipitate size and increases the hardness in the early stages of electropulsing, but the grain and precipitate size is increased and the hardness is decreased by continuing electropulsing. Also, the effect of electropulsing treatment variables as well as treated time and number of periods are discussed. It is demonstrated that increasing treated time can accelerate achieving maximum hardness in lower number of periods.

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1. Introduction

Electropulsing treatment is a novel method in which applying high density electron charges causes dramatic changes on the microstructure and mechanical behavior of alloys such as, precipitates distribution, yield strength, elongation and hardness [1].

EPT studies have been carried out on a large variety of materials containing steels [1,2] aluminum alloys [3], copper and copper alloys [4,5], zinc alloys [6], titanium [7—11] and magnesium [12—14].

It has been reported that the application of electropulsing can affect precipitates distribution on grain boundaries namely, formation of precipitation free zones (PFZ) [15] leading to decrease of yield and ultimate tensile strength (UTS), while elongation is increased [1].

Additionally, Jiang et al. [13] found that applying electrical current causes the coupling of the thermal and athermal effects with the direct electron—atom interaction which results in atomic diffusion enhancement. In fact, this enhancement is due to decrease in atomic transition barrier [15]. Consequently, Yang et al. [15] approved that increase in diffusion coefficient accelerates nucleation and growth of grains through recrystallization, which transform microstructure from deformed condition into refined equiaxed grains. The mentioned results are also approved by other researchers [9,14].

Moreover, Hui et al. [7] demonstrated that electron wind forces caused by electropulsing treatment [16] can enhance dislocations mobility. Besides, the electrical current can increase nucleation rate by decrease in the thermodynamic barrier during phase transformation and it can also be concluded from Zhou et al. [17] study that the nucleation rate
alteration is caused by electrical current itself and not by rapid heating. Besides, grain growth is retarded by electrical current, so that smaller grains are obtained [18].

From the other point of view, application of electropulsing prolongs the fatigue life by healing microscale cracks [19], improving corrosion resistance of nickel based alloy and stainless steels [2,15] and promotes formability of titanium alloys [20] and magnesium alloys (AZ31 and AZ61) [12].

The principal aim of this paper is to investigate the effect of electropulsing variables as well as treated time, numbers of periods, total time, samples thickness and temperature on the microstructure evolution and hardness changes of cold-rolled low carbon steel.

2. Experimental method

As shown in Fig.1, commercial low carbon steel sheets with the chemical composition shown in Table 1 were cold-rolled from 3 mm to 2.5 mm, 2 mm and 1.5 mm thicknesses (16%, 33% and 50% reductions, respectively).

Electropulsing setup heats up the specimens by resistance mechanism at the rate of 300 °C/s. Application of pulse is provided by a digital control unit. The finely spot welded thermocouple (K-type) to the specimens helps in measuring temperature, the temperature was read by the rate of 3000 sample per second using the designed data-logger and measurements done three times and the average value reported. These data were concurrently transferred and saved to PC, and the temperature vs. time diagrams were plotted simultaneously during EPT. The electrical pulses could be disconnected by achieving to the desirable temperature in each experiment. After completion, the specimens were cooled using high speed spray of water and air by the rate of —700 °C/s.

The specimen put between the fixtures, which designed simply to relief stress during heating or cooling. In this study, the samples undergo different pulse states. The electropulsing parameters are defined below:

1. The “treated time”, which refers to the time the electrical current is applied at each pulse and is in the range of 0.1—0.5 s;
2. The “delayed time”, which refers to the time the electrical current is disconnected between two consecutive pulses and is 1 s for all of the experiments;
3. The “number of periods”, which means the times that the current is applied to the specimen in an experiment;
4. “Total time” which is the accumulation of the treated times.

In EPT, in order to investigate the effect of time, the specimens were heated up for the total times of 20, 30, 40, 45, 50, 60, 70, 105 and 140 s (Fig. 1).

Tables 2a—c demonstrate different ways of electropulsing in three sheet thicknesses. In each table the main focus was on increasing the total time of electropulsing.

2.1. Microstructure characterization

The microstructure of electropulsed and as-received specimens were characterized by an optical microscope in order to observe grain size evolution and a field emission scanning electron microscope (FESEM MIRA3 TESCAN) to find precipitates size and distribution. The grain and precipitate size was calculated by Average Grain Intercept (AGI) Method and ImageJ Software.

2.2. Hardness

The Vickers hardness was measured using INSTRON DIA TESTOR722 employing 20 kgf for a dwell time of 20 s. Three indentations were made on each sample and the average hardness was calculated.

3. Results

Mechanical and microstructural evolutions will be discussed in the following section. First, microstructural changes as well as grain size, precipitates size and then hardness results will be presented.

3.1. Material and microstructure

The microstructure characterization of the samples including non-electropulsed and electropulsed samples with different treated times, thicknesses and numbers of periods are depicted below. Figs. 2 and 3 demonstrate grain size evolution and precipitates size of samples with three different thicknesses (2.5, 2 and 1.5 mm), respectively, using optical microscope and field emission scanning electron microscope.

3.1.1. Grain size evolution

Fig. 2 can be interpreted from different points of views, primarily, this figure shows that applying electrical pulses up to 20 s leads to grain refinement. According to measurements and Fig. 3, less reduction percentage leads to more grain refinement. To serve as an example, the percentage of grain refinements for samples with 16%, 33% and 50% of reduction are 22.8%, 14.5% and 14.1%, respectively. In the following, continuing EPT for total time of 140 s causes to grain coarsening for the samples. The notable point is approaching the grain size of the sample with thickness of 1.5 mm to its primary grain size after 140 s of EPT.

3.1.2. Precipitates size and distribution

Applying electrical pulses result in changing size of precipitates. In this experiment FESEM images are only captured from the samples with 2.5 and 2 mm thicknesses because as it will be illustrated later, hardness changes which show microstructural evolution are more obvious in 2.5 and 2 mm thickness specimen.

In accordance with grain size evolution, it is obvious in Fig. 4 that electropulsing for the total time of 20 s results in finer precipitates and applying electrical pulses for 140 s makes
Table 1 – Chemical composition of low carbon steel sheet (wt.%).

<table>
<thead>
<tr>
<th>Element</th>
<th>Fe</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.025</td>
<td>0.0155</td>
<td>0.170</td>
<td>0.0112</td>
<td>0.0053</td>
<td>0.007</td>
<td>0.0172</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>0.046</td>
<td>0.0025</td>
<td>0.0041</td>
<td>0.0097</td>
<td>0.002</td>
<td>0.0045</td>
<td>0.0064</td>
<td>0.0034</td>
<td>0.0032</td>
</tr>
<tr>
<td>As</td>
<td>0.0029</td>
<td>0.0011</td>
<td>0.00016</td>
<td>0.00052</td>
<td>0.0068</td>
<td>0.0013</td>
<td>0.0029</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 2a – Pulse treatments on 16% deformed sheet.

<table>
<thead>
<tr>
<th>Treated time (s)</th>
<th>Number of periods</th>
<th>Total time (s)</th>
<th>Hardness (HV 20 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without EPT</td>
<td>—</td>
<td>—</td>
<td>154</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>150</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>0.3</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>150</td>
<td>105</td>
</tr>
<tr>
<td>9</td>
<td>0.7</td>
<td>200</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 2b – Pulse treatments on 33% deformed sheet.

<table>
<thead>
<tr>
<th>Treated time (s)</th>
<th>Number of periods</th>
<th>Total time (s)</th>
<th>Hardness (HV 20 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without EPT</td>
<td>—</td>
<td>—</td>
<td>174</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>400</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>150</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>0.3</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>150</td>
<td>105</td>
</tr>
<tr>
<td>9</td>
<td>0.7</td>
<td>200</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 2c – Pulse treatments on 50% deformed sheet.

<table>
<thead>
<tr>
<th>Treated time (s)</th>
<th>Number of periods</th>
<th>Total time (s)</th>
<th>Hardness (HV 20 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without EPT</td>
<td>—</td>
<td>—</td>
<td>193</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.1</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>150</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>0.3</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>0.7</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>150</td>
<td>105</td>
</tr>
<tr>
<td>9</td>
<td>0.7</td>
<td>200</td>
<td>140</td>
</tr>
</tbody>
</table>
Fig. 2 – Microstructural evolution of 16%, 33% and 50% deformed sheets without EPT (a—c), with total time of 20 s of EPT (d—f) and with total time of 140 s of EPT (g—i).

Fig. 3 – Grain size evolution vs. total time of applying electrical pulses.
Fig. 4 – FESEM images of (a) 16% deformed specimen without EPT, (b) 16% deformed specimen undergoes 20 s electrical pulse, (c) 16% deformed specimen undergoes 140 s electrical pulse, (d) 33% deformed specimen without EPT, (e) 33% deformed specimen undergoes 20 s electrical pulse and (f) 33% deformed specimen undergoes 140 s electrical pulse.

precipitates coarser and in some situations approximately as coarse as the as-received sample (Fig. 5).

3.2. Hardness

Hardness versus total time curves are presented in Fig. 6(a)—(c) which show an increase in hardness up to 20s of total time and then a drop. Furthermore, Fig. 7 shows the effect of number of pulses on the hardness at different treated times (0.1, 0.3 and 0.5 s). It can be extracted that increasing the number of pulses results in a drop after a notable increase in the range of 50—100 pulses in each three treated times, also hardness peak inclines to the less number of pulses with increasing treated times and a plateau is found after 200 pulses in each treated time.

Fig. 8 shows the aforementioned results from another perspective and illustrates the variation in hardness as a function of the number of electrical pulse and the treated times for 16% deformed sample. It shows that in a specific treated time, the hardness is increased by applying electrical pulses up to 100 times except samples which undergone electrical pulses with 0.5 s of treated time that shows this trend up to 50 number of pulses. On the contrary, continuing this process leads to decrease the hardness in which it can be observed that hardness approaches to its primary hardness in high numbers of electrical pulses.

It is worthy to interpret the hardness alteration with the temperature changes which caused by electropulsing (Fig. 9). Due to direct relation between treated time, number of pulses and temperature of the samples, it can be concluded that
hardness is firstly increased and then drops with temperature increasing. Moreover, it is obvious that the hardness peak is obtained in higher temperatures for the samples with higher reductions.

4. Discussions

4.1. Grain size evolution through applying electrical pulses

For all steels, high heating rates cause to nucleation temperature raising and temperature to complete recrystallization [21], but the main focus in this study is on the investigation of electrical pulses effect on microstructure and hardness of low carbon steel. Therefore, the experiment is designed in a temperature range that no recrystallized grain is observed in the microstructure. It is suggested that applying electrical pulses can decrease potential barriers for nucleation and increase its rate [22]. On the other hand, electron wind force generated by electropulsing [16] makes the dislocations mobile and as a result they consume more vacancies by climbing and gliding along their way. Thanks to electron wind force, dislocations are accumulated on the subgrain boundaries and annihilated at boundaries with small misorientation by climbing and these lead to form more misoriented subgrains. It has been shown that subgrains with larger misoriented boundaries are proper for nucleation and increase nucleation rate. Moreover, it has been reported that electropulsing is weaken Cottrell atmosphere, so electron wind force is more effective in moving dislocations and leads to accumulate them on the subgrain boundaries. Consequently, applying electrical pulses leads to grain refinement in the early stages of electropulsing. Nevertheless, however continuing electropulsing treatment emerges coarser grains due to local rapid rise of the temperature [23]. Increasing the total time of electropulsing increases the sample temperature which provides suitable circumstances for grain growth. Additionally, total time increcent can facilitate annihilation of dislocations by climb and glide, so according to Fig. 2, it is expected to observe coarser grains after a grain refinement in the early stages of electropulsing.

In Fig. 2, it can be seen that 16% deformed sample experiences more drastic grain size alteration in comparison with that of other samples, because firstly due to less dislocation density, mobile dislocations face fewer barriers as well as jungles of dislocations. Therefore, they may accumulate on subgrain boundaries easier and make finer grains by orienting subgrain boundaries and change them into main boundaries. Secondly, with decreasing reduction, thicker samples are obtained, so current density is decreased and because of less temperature increment, precipitation kinetics does not change significantly [24] and consequently less obstacles emerge in the way of dislocations. Therefore, as it was mentioned above finer grains are obtained.

4.2. Effect of electropulsing on precipitates size and distribution

As can be seen in Figs. 4 and 5, electropulsing refines precipitates size at under-recrystallization temperatures. Electropulsing increases nucleation sites and decreases growth for the early stages of the EPT procedure. From another point of view, growth kinetics is increased and precipitates growth kinetics is decreased in the early stages of electropulsing, as a result numerous small precipitates form
Fig. 6 – (a) Hardness vs. total time curve of the specimen with 16% reduction. (b) Hardness vs. total time curve of the specimen with 33% reduction. (c) Hardness vs. total time curve of the specimen with 50% reduction.

in the microstructure [17]. Besides, electrons are scattered unevenly around defects by applying electrical pulses into the volume of the samples [25]. The uneven distribution of electrons around the defects leads to formation an anisotropic shielding effect which is against electromagnetic force between an atom and its neighborhood that results in barrier kinetics drop. In agreement with the former sayings, Eq. (1) proves that the reduction of kinetics barrier ($\Gamma E_k$) increases
the mobility and the accelerated effect of EPT promotes microstructure evolution. Electropulsing owe to enhanced mobility can either lead to coarsening or refinement of the precipitates, however, Lu et al. [26] demonstrated thermodynamically that precipitates refinement can be achieved.

\[
M = M_a \exp \left( -\frac{\Delta E_K}{KT} \right)
\]

where \(M_a\) is the pre-exponential factor, \(\Gamma E_K\) is the kinetics barrier, \(K\) is the Boltzmann constant and \(M\) is the mobility. By the same, it becomes obvious that atoms diffusion coefficient is decreased due to dislocations annihilation by electropulsing, so growth is retarded and finer precipitates are obtained [27].

\[
D = D_0 \left[ 1 + \gamma \frac{D_d}{D_0} \right] (\text{2})
\]

where \(D_d\) is the diffusion coefficient on dislocations, \(D_0\) is the diffusion coefficient out of dislocations, \(\gamma\) is the dislocation density and \(c\) is the radius of dislocation cylinder.

Adversely, after 140 s of electropulsing, precipitates coarsening is obvious. As it said former, electropulsing brings temperature accumulation which increases diffusion coefficient and can lead to precipitates growth. Moreover, temperature accumulation is due to applying more electrical pulses, therefore beside temperature accumulation, time increment allocates more chance to the atoms to diffuse and form coarser precipitates. Also, precipitates coarsening is confirmed by Wang et al. [28].

### 4.3. Hardness evolution during electrical pulse treatment

In this process, promoted hardness is obtained with increasing total electropulsing time up to 20 s (Fig. 6(a)—(c)).
Many elements can be defined as the reasons of hardness improvement. According to what described before, precipitates refinement occurs due to decreasing barriers kinetics [16] or because of an anisotropic shield effect [26] in the early stages of electropulsing, they become more dispersed. These particles make dislocations more difficult to move and this increases the hardness [29].

Excessive increase in hardness by electropulsing can be obtained by “dislocation source limited strengthening” mechanism [30]. The basic idea of this mechanism is that dislocation resources in the interior of grains become weak during grain refinement and some dislocation sources annihilate by a simple annealing process and other remaining dislocation sources become more resistant to yield [31]. Furthermore, dislocation recovery which happens in the present of electron wind force can be another reason of hardness increase. From another perspective, dislocations, which are as a fast route of diffusion for atoms, are destroyed by electropulsing, so precipitates growth is retarded [28].

Additionally, referring to Fig. 2, grain refinement is observed in the first 20 s of electropulsing, hence according to Hall—Petch equation, the hardness is increased [32] as well as yield strength.

In accordance with grain evolution, hardness is decreased in all samples with applying electrical pulses after 20 s, this is in agreement with grain coarsening and precipitates growth that reduce the hardness [33].

It is noteworthy to name PFZ as an effective mechanism of hardness drop that plays an important role in weakening the materials properties after electropulsing [1]. It has been shown in Eq. (3) that increasing heat treatment time has a direct relation with the width of PFZ [34]:

\[
W = Kt^{1/2}
\]

where \( W \) is the width of the PFZ, \( K \) is a constant and \( t \) is the heat treatment time.

Also, temperature accumulation that mentioned as one of the most important reasons of precipitate growth may help PFZ in decreasing hardness.

Electropulsing treatment also leads to spheroidization of cementite plate in large number of pulses [1]. Spheroidization during electropulsing treatment can result in softening of the material which causes the Vickers hardness reduction [23].

### 4.3.1. Treated time duration and number of period effects on hardness

Many researchers studied the electropulsing treatment variables such as number of periods on mechanical and microstructural properties of different materials as well as microstructural evolution of pearlite—ferrite steels [35], interlamellar spacing and mechanical properties of a hot-rolled medium carbon steel [1] and, physical and mechanical properties of magnesium strips [36].

The 16% deformed samples were undergone different treated times (0.1, 0.3 and 0.5 s) for 50, 100, 150, 200, 300 and 400 times (Fig. 7). With regard to Section 4.2, hardness increasen in the early stages can be a result of barriers kinetics energy reduction and precipitates nucleation kinetics increment due to the presence of small clusters of vacancies. Moreover, dislocation recovery can lead to decreasing in precipitates size and causes hardness increase. Furthermore, formation of an anisotropic shielding layer around the atoms enable them to move with lower level of energy. Electrical currents can affect Cottrell atmosphere. Existence of C and N atoms in the microstructure of steel results in Cottrell atmosphere [37], which locks the dislocations, however, electrical current weakens this atmosphere with increasing diffusion. It can result in dislocation recovery next to electron wind force and reduce diffusion routes, therefore finer and more disperse precipitates form and the hardness is increased.

As it was mentioned before, increasing aging time, temperature increasen which leads to the formation of PFZ because of vacancies migration, and time increasen after 100 times of
electropulsing allocate more time and energy to the atoms to form coarser precipitates.

Inclination the hardness peak to the least number of periods with increasing treated time can be as the most important result of this figure. Increasing treated time means that microstructure undertakes longer electrical current, so because of the presence of atoms in this situation for longer times and higher temperatures, atoms can diffuse more easily and form coarser precipitates. On the other hand, vacancies are able to migrate to the interior of the atoms and form PFZ. As a result, this issue is justifiable by Dolinsky et al. [38,39] and Qin et al. [40] model, where $\Gamma'\text{We}$ is defined as a system free energy which is affected by electrical current.

$$\Gamma'\text{We} = I1 / 4rg3/4 (IY_1IY_2)J^2 I'V$$

where $I1/4g$ is the magnetic sensitivity, $g$ is the geometric factor, $J$ is the current density, $I'V$ is the volume of nuclei, $I3/4 (IY_1IY_2)$ is a factor that is related to electrical properties of nuclei, $IY_2$ is the conductivity of the phase that is affected by current and $IY_1$ is the conductivity of the primary phase. The sign of $\Gamma'\text{We}$ is dependent on $I3/4 (IY_1IY_2)$.

$$I3/4 (IY_1IY_2) = \frac{IY_2 - IY_1}{IY_1 + 2IY_2}$$

while applying electrical current, $IY_2$ is less than $IY_1$, therefore $\Gamma'\text{We}$ will be negative and electrical current reduces thermodynamic barrier energy. Finally, it can be concluded that, electrical pulses with 0.5 s of treated time has a more negative value of $I3/4 (IY_1IY_2)$ than 0.3 s of treated time, one so thermodynamic barriers energy reduction becomes more with increasing treated time. Hence, nucleation is more severe in 0.5 s of treated time. On the other hand, increasing current density in a specific period of time in 0.5 s of treated time may lead to stronger anisotropic shielding effect and causes more reduction in kinetics barriers energy and increasing atoms mobility. As a result, with increasing treated time hardening occurs faster and hardness peak can be observed in less pulse numbers. This procedure has the same effect of reduction in specimen area, therefore, with increasing the treated time, the hardness reduction is obtained faster.

4.3.2. Electropulse-induced temperature effect on hardness

The temperature rise induced by electropulsing occurs because of the presence of atoms and solute atoms in the microstructure. It can help atoms and vacancies to diffuse and cause mechanical properties changes [18]. According to Fig. 8 the most outstanding point is shifting the hardness peak to the higher temperatures with increasing reduction. It can be resulted from higher dislocation density in 50% deformed sample in comparison with that of 33% and 16% deformed samples. This issue may retard grain and precipitate refinement by putting difficulties in front of dislocation movement, therefore in higher temperatures dislocations are annihilated and accumulated on subgrains. From another point of view, it is illustrated that hardness incessant rate is less effective than hardness drop. Diffusion coefficient is directly affected by temperature and increased with increasing temperature [41]. In low temperatures, more times are needed for atoms and vacancies to diffuse and increase hardness, on the other hand, in high temperatures, in shorter time the hardness is decreased and in some cases the hardness becomes less than the primary hardness.

5. Conclusions

Electropulsing treatment is performed on cold-rolled low carbon steel in order to examine the microstructure and hardness improvement. The following conclusions are obtained:

1. Electropulsing treatment can lead to grain refinement in the early stages and grain coarsening by continuing this treatment. This phenomenon is more observed in less deformed samples.
2. In accordance with grain evolution, precipitates experience refinement up to 20 s of electropulsing and becomes more disperse. Applying electrical current up to 140 s leads to precipitates growth.
3. With increasing the treated time, the hardness peak is obtained in the less numbers of pulses, and after 400 number of pulses a dramatic drop is observed. Also, increasing the treated time causes more drop and in some cases the final hardness is less than the primary hardness.
4. With increasing reduction percentage, the hardness peak is achieved in higher temperatures.
5. The maximum grain refinement and hardness improvement are achieved by applying the electrical pulses for a total time of 20 s with a treated time of 0.5 s on 16% deformed samples.

Conflicts of interest

The authors declare no conflicts of interest.

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