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Electropulse-induced microstructural evolution in a ferriticpearlitic 0.14% C steel

A. Rahnama
Department of Materials, Imperial College London
Exhibition road, London, SW7 2AZ, England
R.S. Qin,
Department of Materials, Imperial College London
Exhibition road, London, SW7 2AZ, England

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Steels consisting of pearlite are extensively used in various engineering and commercial applications since they possesses a good combination of strength and ductility as well as other useful material properties such as corrosion resistance, wear resistance, weldability and machinability. The stress-strain behaviours of ferritic-pearlitic steels strongly depend on its constituent phases: ferrite governs the ductility whereas pearlite phase controls the strength [1]. The relationship between microstructure and mechanical properties of these steels have been investigated by many researchers [1, 2, 3]. Various colonies of pearlite have different lamellae orientations. These cementite lamellae are frequently paralleled and curved and the interlamellar spacing varies in size from colony to colony [2]. Hence, pearlite microstructure can be tailored by variation of the interlamellar spacing which directly affects the strength [3].

It is known that the application of electric current pulses to metallic materials affects materials plasticity [4], recrystallization [5], structure relaxation [6], casting microstructure [7, 8] and fatigue life [9]. For Fe-3wt% Si alloys, electropulse has been found to promote the Goss-texture development during recrystallization [11, 23]. Theoretically, electropulse is found affecting the kinetic barrier and free energy sequence of phases. The former includes the phase transformation at a lower than ordinary temperature [12] and the enhanced diffusivity [17]. The latter includes the electropulse-induced new phase [14] and new microstructure formations [15]. In the present work, electropulse-induced cementite plates rotation in ferritic-pearlitic steel was observed. This reveals a new mechanism that has not been covered in literature. Application of Electropulsing in the process of ferritic-pearlitic steel may provide a new way to enhance mechanical properties by altering the pearlite transformation and microstructure.

The steel was prepared via the conventional ingot metallurgical routine and the chemical composition in weight percentage of the alloy was found to be 0.14 C-1.0 Si-2.1 Mn-0.03 Al-0.025 Nb and balance iron. The ingot was rolled at $800°C$ to a sheet with 2.64 mm thickness and then chilled slowly in furnace. Its microstructure at ambient temperature consists of mainly the polycrystalline ferrite grains and a small amount of cementite scattered among the ferrite. The sheet was cut into many 30 mm(longitudinal length) $\times$ 3.42 mm (width) $\times$ 2.64 mm (thickness) samples and grouped randomly for subsequent electropulsing treatment.

The electropulse was generated by an Avtech AV-108F-B-P Current Pulser which converted the direct current into pulsed current. The direct current power source has standard output power of 80 watts and standard output electric potential of 20 volts. The pulse width, peak current intensity, pulse frequency and pulse trigger mode are programmable. The testing steel sample was connected with two copper electrodes from both ends to form a current circuit. No internal stress might occur if there was a current-induced temperature rising because both sample and electrodes were hold freely rather than fixed to certain positions. An oscilloscope was equipped in the circuit for monitoring the electropulse signal. All the pulses applied in this work were chosen to have $20\mu s$ pulse width and $1.018 \times 10^7 A/m^2$ peak current density. The frequency of electropulse was 1 Hz. Two different samples were electropulsed at these conditions each of which with a different number of pulses, 100 pulses (denoted as EP1), 1000 pulses (EP2).

The microstructure of the samples before and after electropulsing treatment were characterised by optical microscope and a LEO Gemini 1525 high resolution field emission gun scanning electron microscope (FEGSEM) operated at 5kV. The samples for scattering electron microscopy (SEM) observations were prepared by the conventional method using diamond pastes and etched in 2% nital etching solution. The volume fraction of phases determined using point counting technique and was measured to be 84.5%. It was done through 30 randomly selected fields at a magnification of $\times$100 in the optical microscope. The interlamellar spacing was measured using FE-SEM technique as described in Ref.[16]. On average, 50 pearlite colonies in each sample were characterized for calculating the interlamellar spacing using this technique. The Vickers hardness was measured using a Zwick digital 3103 IRHD Micro Compact Hardness Tester employing 10-kg load for a dwell time of 10 s.

Fig.1a demonstrates the scattering electron microscopy of the unelectropulsed specimen. Microstructure consists of ferrite and closed-packed plates of cementite. The lamellae are randomly distributed into the ferrite matrix and the directions of plates do not show any preference (indicated by red circles). The interlamellar spacing was measured to be $52\,nm$. After 100 electric current pulses (EP1), the overall microstructural change was insignificant (Fig. 1b). However, as it is evident from Fig.2, the interlamellar spacing of pearlite is increased. For this sample on average, the increase in the interlamellar spacing of pearlite was measured to be $96\,nm$. Moreover, spheroidization occurred as it can be seen on the top right of Fig.2b. After 1000 pulses (EP2), there is a remarkable change in microstructure (Fig.1c). The nodules were mostly aligned with the current direction and those which were not in the direction of electric current were fragmented. The interlamellar spacing was, also, increased to 251 nm.

The Vickers hardness test measured on the original sample and two electropulsed specimens shows a decrease in its value and substantial softening in the structure. The Vickers hardness value of the as-received specimen was 232 HV_{10} while that of EP1 and EP2 were measured to be 210 and 181 HV_{10}, respectively. The hardness value of the EP-1, for which the microstructural change was trivial, dramatically decreased comparing with that of as-received. The decrease in Vickers hardness value is consistent with the spheroidisation of lamellar structure observed in SEM examinations. The spheroidization of pearlite and subsequent reduction in hardness value have been, also, reported for a severly deformed eutectoid steel [17].

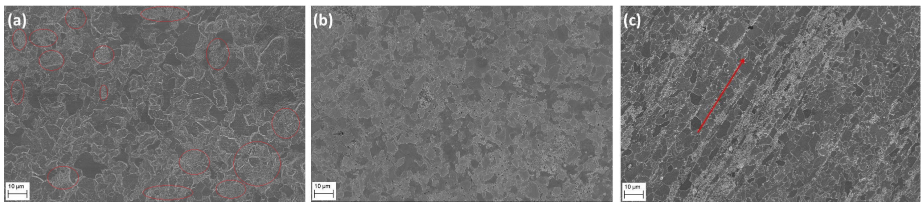

Figure 1: SEM micrographs showing the microstructural evolution during electropulsing treatment. (a) The specimen before the treatment (b) EP1 (c) EP2 (the red arrow shows the the current direction).

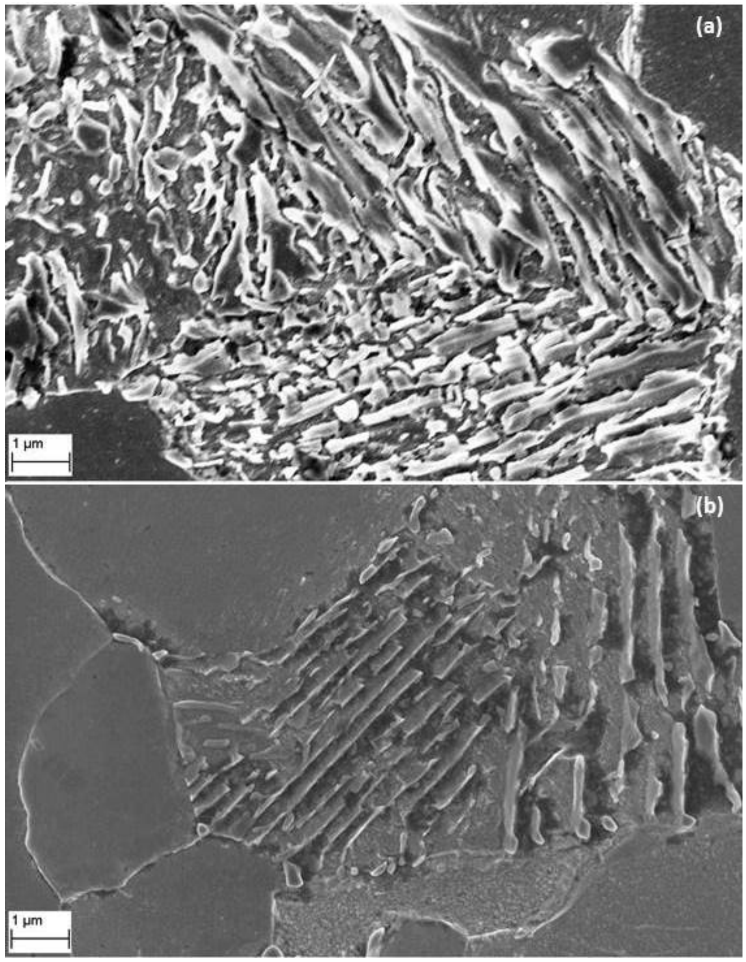

Figure 2: The increase in the value of interlamellar spacing of pearlite after electropulsing treatment where (a) shows the mcirostructure of unelectropulsed sample while (b) demonstrate the microstructure of the sample after 100 times of pulses.

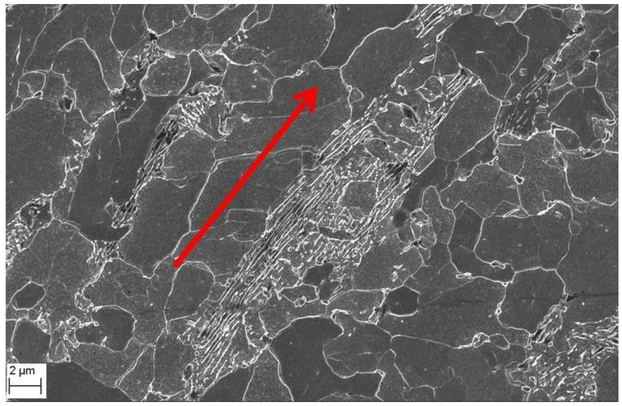

Figure 3: The formation of lamellar structure parallel to the electric current direction in EP2 (the red arrow shows the flow direction of the electric current).

It is well-known that electropulsing treatment affects the kinetic of the transformation. Electropulsing increases the diffusivity of carbon atoms due the electron wind effect. It has been learnt that electromigration of carbon can occur in iron at current density as low as $10\ Acm^{-2}$ [4]. Moreover, high dislocation density and high stored energy resulted from rolling provide high electromigration and enable carbon to diffuse rapidly. Furthermore, vacancies play a key role in precipitation mechanism since they act as nucleation sites for the carbide precipitate [18]. Electropulsing treatment also results in the local rapid rise of the temperature and thus generates huge amount of vacancies which are originated from dislocations, interphase and grain boundaries [17]. All the mentioned mechanisms could, then, account for the enhanced diffusion in the steel and aid to accomplish the kinetic requirements for the phenomenon observed in this study.

Before considering this transformation in terms of free energy change, it is worth to investigate how the treatment changes the electrical resistivity of the steel. Thermodynamic calculations show that the electropulsing treatment encourages a structural evolution in materials towards the state with lower electrical resistance [19]. Since the geometric morphology of the phases and their spatial configurations affect the electrical resistivity of the steel [20], electropulsing tends to configure the structure in a way through which the electrical resistivity becomes lower. This is schematically shown in Fig.4. In the steel under study, the electrical resistivity of cementite (ρ_c) is much larger than that of ferrite (ρ_f) due to its high carbon and low iron composition. In addition, the interconnected cementite plates increases the overall electrical resistivity of the steel. Fig.4a schematically illustrates the microstructure of unelectropulsed sample with a total resistance of $R_a = \frac{\rho_C L}{S}$, where L is the total length of the sample and S is the cross section area. After electropulsing, Fig.4b, the total electrical resistance can be approximated as $R_b = \frac{\rho_F L}{S_{gap}}$, where S_{gap} is the gap area between the fragmentated plates. As shown in Fig. 4, the value of S_{gap} in Fig.4c and d is larger than that of S_{gap} in Fig.4a. Hence, it can be concluded that $R_a > R_b > R_c > R_d$. Fragmentation of the lamellae and formation of discontinuous spherical cementite particles, therefore, promotes the formation of more percolation routines within the ferrite network. Electric current pulses makes the cementite lamellar to break into small spheres and force the phases to arrange as illustrated in Fig.4d in order to decrease the total electrical resistivity.

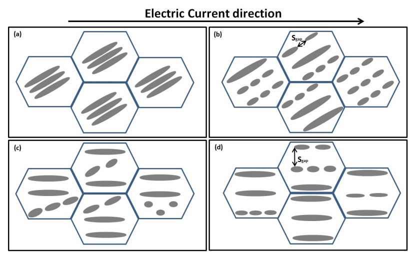

Figure 4: Schematic diagram illustrating various configurations of pearlite microstructure.

In the classical theory of electropulse-induced microstructure transformation, electric current contributes an extra term to the system free energy ΔG_e [19]. Electric current pulses passing through a material introduces a free energy G_e which can be expressed as following [20, 21]:

$$G_e = -\frac{\mu}{8\pi} \int \frac{\overrightarrow{j}(r).\overrightarrow{j}(r')}{|r-r'|} dr dr' \tag{1}$$

where r and r' are two different positions in space. $\overrightarrow{j}(r)$ and $\overrightarrow{j}(r')$ are the current densities at position r and r', respectively. μ is the magnetic permeability. The configuration of the lamellar structure strongly affect the electric current distribution as its electrical resistivity is much higher than that of ferrite. Hence, various configuration of the lamellar structure corresponds to different free energy G_e. When a cementite plate breaks into the smaller pieces altering the current distribution from $\overrightarrow{j_1}(r)$ to $\overrightarrow{j_2}(r)$, the associated free energy change can be expressed as [20, 21]:

$$\Delta G_e = \frac{\mu}{8\pi} \int \int \frac{\overrightarrow{j_1}(r)\overrightarrow{j_1}(r') - \overrightarrow{j_2}(r)\overrightarrow{j_2}(r')}{|r-r'|} d^3r d^3r' \tag{2}$$

ΔG_e will be negative when the electrical resistivity of new microstructure is less than that of the original microstructure and vice versa. This has been applied to explain the electropulse-promoted Goss-texture in silicon steels [23]. Moreover, quantitative calculations of ΔG_e reveal the important roles that plays in interfacial reactions, precipitations and recrystallizations [4], inclusion segregation [21], and phase transformation [22]. This theory can be, also, used to explain the electropulse-induced microstructural evolution in the steel under study. When an electric current is passing through this ferritic-pearlitic, some plates are oriented in a way that their lowest resistivity direction aligned with the current direction but other are not. Since the electrical resistivity increases significantly by scattering of electrons, the lowest resistivity direction is aligned with the current direction. Those plates with their smallest resistivity direction not aligned with the current flow direction will adjust their orientation in order to minimum the free energy associated with electric current. The free energy difference is the driving force for the alignment of cementite plates from a thermodynamic point of view. Because the cementite possesses larger resistivity than that of ferrite, the value of ΔG_e, reduces as the cementite plates are fragmented. Formation of the new plates aligned with electric current can decrease this value even more since in this configuration, the collision between electrons and nodules will be at its lowest level.

In summary, electropulsing treatment leads to fragmentation of lamellar structure. Further electropulsing results in the formation of cementite plates in the direction of electric current as to reduce the system free energy to its lowest level. This study has not been preceded before and therefore put a new light on the effect of electropulsing treatment on the microstructural evolution. Electropulsing treatment shows a promising potential as a processing method for developing customized microstructure and enhanced performance in ferritic-pearlitic steels.

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