Austenite Grain Ultra-refinement of 42CrMo Steel Induced by Electropulsing Treatment

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Abstract. With the increasing demands for steel products with both higher strength and toughness to meet the requirements for weight reduction and security promotion, steels with fine grained microstructures cannot meet the application demands any more, and should be further strengthened without toughness or other property loss, such as fatigue lifetime. Ultragrain refinement is a promising way to strengthen steels without toughness loss. For steels with the final bainite, martensite or tempered martensite structures, microstructure refinement basically depends on the prior austenite grain size reduction. In this study, electropulsing treatment (EPT) was used to refine the austenite grain, because pulse current shows remarkable influence on microstructure of metallic material. Results in this study confirm that the prior austenite grains (PAGs) can be ultra-refined by pulse current. When the steel was quenched from peak temperature less than about 850℃ during EPT, the average PAGs size was less than 5μm. With the increasing of peak temperature during EPT, the PAGs became coarsening. But the PAGs in samples quenched from peak temperatures less than 1000℃ were still finer than that quenched from recommend 850℃ during conventional heat treatment (CHT). EPT induced grain refinement is related to the thermal effect and athermal effect of high density pulse current. The thermal effect results in high heating rate as high as 7700℃/s. In order to analysis the influences of rapid heating effect and athermal effect of pulse current itself on the grain refinement, J Mat Pro software was used to calculated the PAGs size at the same heating rate as that during EPT, which represented the nucleation rate and grain size only under the influence of thermal effect related to rapid heating. However, the simulated result shown the PAGs cannot be ultra-refined during simplex rapid heating. This reveals that the athermal effect of high density electric current itself plays a key role in the EPT induced austenite grain ultra-refinement.

1. Introduction

Grain refinement in steels can give rise to the increase of strength levels without sacrificing toughness[1]. Conventional rolling, characterized by its offline post-rolling heat treatment, can obtain moderate grain refinement potency. The ferrite grain size, obtained via commercial thermomechanical processing techniques, is limited to 5μm [2]. According to the prediction of Hall-Petch equation, if the average ferrite grain size is refined from 5 to 1μm, the yield strength of a given steel should be increased by up to 350MPa[2]. Consequently, various techniques and processes, such as severe plastic deformation (SPD) [3] and advanced thermomechanical processes[4], have been developed to produce ultrafine-grained ferrite steels. For steels with the bainite, martensite or tempered martensite microstructures, grain refinement is focused on the size reduction of austenite grains. However, development of austenite grain ultra-refinement is not as booming as that for ultrafine grained ferrite
steels. It is impracticable to obtain ultrafine austenite grains by heat treatment due to its low nucleation rate during austenite transformation. Austenite grain size usually ranges from tens microns after CHT. Ultrafine austenite grains can be produced by cyclic heat treatment[5-8], dynamic recrystallization[9, 10], annealing of cold rolled stainless steel[11] and SPD[12]. But cyclic heat treatment is verbose and energy wasting. Ultragrain refinement of austenite via recrystallization or annealing of the deformed structures needs high plastic straining, produced by high reduction cold rolling, which needs high deformation loads.

It was reported that the nucleation rate can be dramatically improved by implying high density electropulsing during phase transformation[13]. Zhao et al.[14] reported that the tensile strength of 22MnB5 steel was improved to 2022MPa after EPT, 469MPa higher than that of the hot stamped sample, and the elongation was maintained. They reported this excellent property was attributed to the refinement of martensitic laths, resulted from austenite grain refinement induced by EPT. Zhou et al.[15] reported that ultrafine grained ferrite microstructure was formed after EPT, and the strength of tested steel was enhanced without the decrease in ductility. It was discussed that EPT can increase the austenite nucleation rate, which was the essential reason for microstructure refinement and property improvement[14-16]. But few efforts have been made directly to study the austenite grain refinement potency of EPT in steel. In this study, effect of EPT on the austenite grain size has been investigated.

2. Experimental Procedure
Commercial 42CrMo steel (0.43wt.%C, 1.04Cr, 0.18Mo, 0.23Si, 0.61Mn, 0.002S, 0.013P, Bal. Fe) was used as the tested material in this study. The as-received 42CrMo steel samples was austenitized at 850°C for 10min in the vacuum tube furnace, followed by oil quenching. After tempering at 500°C for 30min, those samples were subjected to EPT. The discharging duration and pulse current density were controlled by a program on computer (Table 1). At the end of the discharging duration, the sample was quenched by oil spraying immediately. Temperatures of the specimens were measured by infrared thermometer. Figure 1 shows the schematic illustration of the EPT system.

Optic metallographic samples were prepared through standard procedure. The samples were etched with the ethanol+4vol% nitric acid solution. The prior austenite grain boundaries were revealed using Picral reagent. The average grain size of each sample, measured by Image-pro plus 6 software, was taken from more than 20 images examined at different fields with a magnification of 1000 times.

| Peak current density (MA/m²) | 1700 |
|-----------------------------|------|
| Discharging duration (ms)   | 100  | 105 | 110 | 115 | 120 | 125 | 130 | 140 |
| Peak temperature (°C)       | 790  | 814 | 843 | 895 | 920 | 961 | 1008| 1085|
3. Results

The microstructure of the as received 42CrMo steel consisted of ferrite and pearlite (Fig 2a). After quenching from the austenitization temperature of 850°C during heat treatment, the steel consisted of martensite. During tempering at 500°C, the martensite structure decomposed. The average PAGs size of the sample quenched from 850°C during heat treatment was 31μm.

The Ac₃ temperature of the tested 42CrMo steel is 791.2°C according to the model build by Kasatkine et al.[17] As quenched from the peak temperature of 790°C during EPT, the microstructure consisted of martensite (Fig. 3a). This meant that the starting tempered structure had transformed into
austenite upon heating during discharging. But the metallographic morphology of martensitic lath cannot be revealed clearly by ethanol+4vol% nitric acid solution. This was probably due to the formation of cryptocrystalline martensite because of PAGs size reduction. The average austenite grain size was ultra-refined to 3.3μm (Fig. 4 and Fig. 5). The hardness of EPT-790℃ sample was improved to 63HRC (Fig. 6). While the hardness of the sample quenched from 850℃ during CHT was 56.7HRC. With the increasing of peak temperature during EPT, the austenite grain size increased. But compared with the CHT-850℃ sample, the PAGs size of samples quenched from peak temperature less than 1000℃ during EPT was still smaller. With the PAGs growing, the martensitic structure become coarsening after quenching (Fig. 3).

![Fig. 3. Optic microstructures of 42CrMo samples quenched from various peak temperatures during EPT: (a) 790℃, (b)814℃, (c)843℃, (d)895℃, (e)920℃, (f)961℃, (g)1008℃, (h)1085℃.](image1)

![Fig. 4. Prior grain boundaries of 42CrMo samples quenched from various peak temperatures during EPT: (a) 790℃, (b)814℃, (c)843℃, (d)895℃, (e)920℃, (f)961℃, (g)1008℃, (h)1085℃.](image2)
Fig. 5  Average prior austenite grain sizes of 42CrMo samples varying with quenching peak temperatures during EPT.

As high density pulse current passes through samples, Joule heat effect will result in rapid heating. In this study, the heating rate was 7700°C/s. High heating rate not only can result in the rising of Ac₃ and Ac₁ temperature[18], but also could result in grain refinement[19]. In order to analysis the grain size at rapid heating without the influence of high density current, J Mat Pro 10 software was used to simulate the rapid heating. The simulation results shown that the finishing temperature of the austenite transformation was 971°C, when the heating rate (Vₛ) was 7700°C/s. And the austenite grain size at 971°C was 6.8μm (Fig. 5). This indicates the austenite grains cannot be ultra-refined if EPT is just regarded as a simplex heat treatment with high heating rate.

4. Discussion
The nucleation and grain growth of austenite during EPT was influenced by the coupling of thermal and athermal effects of high density pulse current. In a current-carrying system, the free energy change is described by formula[14, 15, 20]: 
\[ \Delta W = \Delta W_0 + \Delta W_e \] 
\[ \Delta W_0 \] is the free energy change in a current-free system, \( \Delta W_e \) is the free-energy change in a current-carrying system. \( \Delta W_e \) can be given:

\[ \Delta W_e = \mu_0 g(a, b) \xi(\sigma_1, \sigma_2) j^2 \Delta V \]

\( \mu_0 \) is the magnetic susceptibility in vacuum, \( g(a, b) \) is the geometric factor, \( \xi(\sigma_1, \sigma_2) \) is a factor that depends on the electrical properties of the nucleus and the matrix, \( j \) is the electric current density, \( \Delta V \) is the volume of a nucleus. \( \xi(\sigma_1, \sigma_2) \) can be written as

\[ \xi(\sigma_1, \sigma_2) = \frac{\sigma_2 - \sigma_1}{\sigma_1 + 2\sigma_2} \]

In the temperature of \( \alpha \rightarrow \gamma \) phase transformation, \( (\sigma_1 = \sigma_\gamma > \sigma_2 = \sigma_\alpha) \)[15], where \( \sigma_\gamma \) and \( \sigma_\alpha \) is the conductivity of \( \gamma \) and \( \alpha \) phase respectively. Thus \( \xi(\sigma_1, \sigma_2) < 0 \)[14, 21]. Generally as \( b >> a \), so \( g(a, b) \) is positive. The sign of \( \Delta W_e \) is determined by \( \xi(\sigma_1, \sigma_2) \), that is \( \Delta W_e < 0 \). This implies that electropulsing can decrease the thermodynamic energy barrier of \( \alpha \rightarrow \gamma \) phase transformation.

The relationship between the nucleation rate (\( I_e \)) in a current-carrying system and the nucleation rate (\( I_0 \)) in a current-free system is described as[14]:

\[ I_e = I_0 \exp(-\Delta W_e \kappa^{-1} T^{-1}) \]

where \( \kappa \) is Boltzmann constant, \( T \) is temperature. Due to \( \Delta W_e < 0 \), so \( I_e > I_0 \), which means that electropulsing can increase the nucleation rate of \( \gamma \) phase. The ultra-grain refinement potency of EPT, based on the experimental results above, confirms that the austenite nucleation rate can be dramatically improved by pulse current. Owing to the short discharging duration and the high cooling rate during quenching, the austenite grains could not grow up easily when the peak temperature is not too high. However, when the peak temperature exceeded a key temperature, the growing rate of austenite grains was accelerated.

According to the Joule heat effect of electric current, the temperature rise can be calculated by formula[14]:

\[ \Delta T = \frac{\rho f^2 (C_p d)^{-1} t}{t} \]

where \( \rho \) is the resistivity, \( C_p \) is the specific heat, \( d \) is the density, \( t \) is the duration of discharging. In this study, the heating rate during EPT was 7700°C/s. The simulation results shown that the nucleation rate cannot meet the requirement for ultragrain refinement even
during rapid heating if without the effect of pulse current. In other words, this result indicates the ultragrain refinement potency of EPT is not attributed to the rapid heating induced by Joule heat effect of pulse current, but owing to the athermal effect of pulse current itself. Moreover, the athermal effect of pulse current also affected the phase transformation temperature, resulted in the decreasing of austenite transformation finishing temperature, compared with that during rapid heating without the effects of electric current. Seeing that the grain growth rate versus peak temperature was greater during EPT, compared with that during rapid heating, based on the simulation results, the austenite grain kinetics could be enhanced by the athermal effect of pulse current. However, in order to understand the detailed role of the athermal effect of high density pulse current on the austenite transformation and grain growth kinetics, more experimental studies should be made.

5. Conclusion
The microstructure in 42CrMo steel after EPT was studied. The starting tempered microstructure transformed into austenite upon heating during EPT at the peak temperature about 790℃. The PAGs were ultra-refined when quenched from peak temperature less than about 850℃. However, austenite grains cannot be ultra-refined during simplex rapid heating according to the simulation result. The EPT induced austenite grain ultra-refinement is attributed to the athermal effect of high density pulse current itself, which can dramatically improve the nucleation rate during austenite transformation. Results in this study provides an effective method to ultra-refine austenite grains for steel with the final bainitic, martensitic or tempered martensite structures, whose PAGs cannot be ultra-refined heat treatment easily.

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