Effect of Starting Microstructure in High Speed Steel on the Grain Refinement Potency of Electropulsing Treatment

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Abstract: High speed steels (HSSs) are widely used materials for tools production, which grab a third part of the global cutting tool market. Heat treatment is an indespensable process for the fabrication of HSS tools. Modifications of carbides and grain size of the matrix are two main aspects for the heat treatment of HSSs. In order to obtain better wear property, hardness or red hardness, modification of carbides attracts more researchers’ attention, but grain refinement benefits to the toughness and tool life. Compared with the grain refinement methods used for other steels, such as controlled rolling, available method for grain refinement of HSSs seems deficient. Our previous study provided a new method to produce ultrafine grained M2 steel, but the effect of the starting structures on the grain refinement potential of electropulsing treatment (EPT) was not involved. Results in this work show that the grain size can both be refined or even ultra-refined by EPT, whatever the difference in the starting structures. But the austenite transformation of the matrix was completed at lower peak temperature when using starting tempered structure. And the pre-tempered M2 samples have higher hardness than that obtained after heat treatment or EPT when using the starting annealed structures.

1. Introduction
High speed steels are alloys of complex Fe-Cr-C-X system, where X represents different strong carbide forming elements, such as W, Mo, Cr, V, or Co[1, 2]. Due to their excellent wear resistance, high red hardness and good toughness, HSSs are important industry materials and widely used for cutting tools, molds and rollers[1-3]. The mechanical properties of HSSs basically depend on the conditions of carbides, as well as the grain size of the matrix. Modification of carbides in HSSs has been intensively studied[1, 2, 4]. But the grain refinement method for HSSs seems scarce.

Grain refinement is a popular subject in modification of microstructure and mechanical properties in steels. But researches on modification of carbides in HSSs attract more attentions than that on grain refinement. This is because morphologies of carbides contribute the red hardness and wear property of HSSs, which is very important for this material used for cutting tools. Nevertheless, grain refinement profits for the improvement of the toughness and tool life[5].

Heat treatment is a vital process to control the grain size in HSSs. Grain size of commercial HSSs ranges from 5 ~ 60μm [6-9], depending on detailed chemical compositions and austenitization temperature. Grain size obtained at low temperature austenitization is finer than that at high temperature austenitization. But in order to obtain sufficient secondary hardening effect during triple tempering, the austenitization temperature must be high enough to obtain higher supersaturated carbon and alloying elements in solution in the matrix before quenching. Therefore, assurance of sufficient carbides dissolution in HSSs is the first important thing during heat treatment. Hence, it seems hard to
refine the grain size and simultaneously promote the dissolution carbides during heat treatment. Our previous study[10] reported a new method by using EPT to produce ultrafine grained M2 HSS. But it is not clear whether the starting structures have effect on the grain refinement of M2 steel after EPT. In this work, the effect of starting structures on the grain size in M2 steel after EPT has been studied.

2. Experimental Procedure
Commercial M2 HSS was used as the tested material in this study. The two starting structure types used for EPT in this work were annealed and tempered, respectively. The as-received M2 steel was annealed, which was used as one type of the starting structures. In order to obtain tempered starting structures, the as-received M2 steel was austenitized at 1180℃ for 10min in the vacuum tube furnace, followed by oil quenching. Then these quenched samples were tempered at 550℃ for 1 hour.

Electropulsing was performed under ambient condition by self-made electropulsing generator. The discharging duration and pulse current density were controlled by the program on a computer. The temperatures during discharging were measured infrared thermometer. Table 1 and Table 2 list the used pulse current parameters and corresponding peak temperatures of samples. At the end of the discharging duration, the sample was quenched by oil immediately. The schematic illustration of the EPT system can be found in our previous work [10]. For comparison, the as-received M2 steel was also treated by conventional heat treatment. The grain size was measured by Image-pro plus 6 software. The final result of each sample was taken from more than 20 images observed at different fields with a magnification of 1000.

Table 1. Pulse current parameters used for the starting annealed structure group.

| Peak current density (A/mm²) | 1700 |
|-----------------------------|------|
| Discharging duration (ms)   | 180  | 190  | 200  | 220  | 230  | 240  |
| Peak temperature (℃)        | 1190 | 1217 | 1251 | 1276 | 1286 | 1308 |

Table 2. Pulse current parameters used for the starting tempered structure group.

| Peak current density (A/mm²) | 1700 |
|-----------------------------|------|
| Discharging duration (ms)   | 170  | 174  | 176  | 182  | 185  | 190  | 193  | 195  | 210  |
| Peak temperature (℃)        | 1034 | 1075 | 1095 | 1138 | 1188 | 1202 | 1218 | 1255 | 1278 |

3. Results
The as-received M2 steel consisted of coarse eutectic carbides and spheroidal pearlite (Fig. 1a). In order to obtain the tempered starting structures, some M2 samples were pre-heat treated. During conventional austenitization at 1180℃ for 10min, most of carbides were dissolved into the matrix (Fig. 1b). But these primary carbides were not dissolved completely. These primary carbides are MC and M₆C types, which precipitate at 1294 and 1288℃ in equilibrium, respectively, much higher than the austenitizing temperature in most cases[11]. So, coarse primary carbides are hardly dissolved completely during heat treatment. The hardness was improved to 64 in HRC after quenching. The average grain size was 18μm. When the quenched sample was tempered at 550℃ for 1 hour, numerous secondary carbides precipitated (Fig. 1c). And the hardness was maintained at 59.3 in HRC.

Figure 1. Microstructures of M2 samples: (a) annealed (as-received), (b) conventional quenched from 1180℃, (c) tempered at 550℃ for 1 hour.
For comparison, the microstructure with the austenitization temperatures during heat treatment are shown in Figure 2. The A1 and Acm temperatures of M2 steel are 795°C and 821°C respectively [12]. When the steel was heated to 1050°C during heat treatment, the matrix transformed into austenite. But a majority of carbides in the starting annealed structures was not dissolved. The supersaturated carbon and alloying elements in solution in the matrix was not high enough to obtain full martensitic matrix during quenching (Fig. 2a). When the austenitizing temperature was increased to 1100°C, most spheroidal pearlitic carbides were dissolved. After quenching the matrix transformed into martensite, and the hardness was improved to 59.4 in HRC (Fig. 3). While quenching from 1150°C, more primary carbides were dissolved, and the newly formed austenite grain boundaries were clearly revealed. With further increasing the austenitization temperature, more primary carbides were dissolved. But the grain size grew coarse further. When quenching from 1286°C, fish born-like carbides network was formed at the grain boundaries (Fig. 2f). The grain size was increased to 81μm (Fig. 4).

Microstructures of M2 samples with starting annealed structures after EPT are shown in Fig. 5. The hardness of the sample quenched from 1190°C during EPT was improved to 56.7HRC (Fig. 3). This indicated the starting structures had undergone austenite transition upon heating during discharging. The A+EPT-1190°C sample consists coarse primary carbides, undissolved pearlite carbides and partial martensitic matrix (Fig. 5a). With increasing of peak temperature during EPT, more and more carbides were dissolved, and the matrix transformed into martensite. When the peak temperature was increased to 1286°C, fish born-like carbides network was formed at the grain boundaries (Fig. 5f).
Figure 5. Microstructures of M2 samples with starting annealed structures after EPT and quenching from peak temperatures: (a) 1190℃, (b) 1217℃, (c) 1251℃, (d) 1276℃, (e) 1286℃, (f) 1308℃.

Microstructures of M2 samples with starting tempered structures after EPT are shown in Fig. 6. It can be found that most of secondary carbides in the starting tempered structures were dissolved when quenched from 1034℃ (Fig. 6a). With the peak temperature increasing to 1095℃, some very fine grained austenite were formed (Fig. 6c). When quenching from 1138℃, the starting matrix had transformed into ultrafine grained austenite. And all carbides were dissolved into the matrix except coarse primary carbides. With the increasing of peak temperature, grain size grew coarse. But when quenching from 1278℃, carbides networks were formed (Fig. 6i). The hardness of M2 samples with starting tempered structures after EPT was stably maintained to ~ 65HRC.
Figure 6. Microstructures of M2 samples with starting tempered structures after quenching from various peak temperatures during EPT: (a) 1034℃, (b) 1075℃, (c) 1095℃, (d) 1138℃, (e) 1188℃, (f) 1202℃, (g) 1218℃, (h) 1255℃, (i) 1278℃.

4. Discussion

Heat treatment is an imperative process for the fabrication of HSS tools. And it was a basic way to control the grain size for a specified HSS. In order to obtain finer grain size during conventional heat treatment, HSSs should be austenitized at lower temperature. But this could decrease the dissolved volumetric fraction of primary carbides. For example, the grain size of M2 steel can be refined to 6μm when quenched from temperature less than 1140℃, but the dissolution of primary M6C carbide can be increased 50% if quenching from 1180℃[9]. So grain refinement in HSSs by lowering austenitization temperature is not a sensible choice.

Previous study[10] and results in this work show that EPT demonstrates remarkable grain refinement ability in M2 steel. The grain size of M2 steel after EPT was much smaller than that after heat treatment (Fig. 4), regardless of the starting microstructure used during EPT. But the ultrafine grained microstructure was obtained at lower peak temperature when using the starting tempered structure. This is probably because of the difference related to the austenite formation mechanisms. The formation of austenite in the starting annealed structures is a diffusion controlled process. This process involves formation of austenitic nucleus and the dissolution of carbides, controlled by the diffusion around the austenite nucleus, matrix and carbide. Acm temperature of the matrix is 821℃, much lower than the peak temperature needed for the actual completion of austenite transformation in the matrix. But the dissolution temperature of carbides, formed during annealing, is higher than the Acm temperature. The temperature needed for the completion of austenite transformation of the matrix during heat treatment is about 1100℃ (Fig. 2b). While the austenite transformation of the matrix was completed at about 1217℃. This is because the heating rate during EPT is much higher than that during heat treatment. High heating rate increases the austenite transformation finishing temperature.
However, the microstructure transformation process in the starting tempered samples was different. Even though this process was also relevant to some diffusion controlled transition, such as the dissolution of secondary carbides in the starting tempered structures, the austenite transformation of the matrix was completed at lower peak temperature, compared with that when using the starting annealed structures. This phenomenon resulted from two reasons. The first reason was related to the formation mechanism of revised austenite. The starting tempered structures could contain residual austenite and un-decomposed martensite. Even new martensite probably formed during cooling from the temperature of tempering, due to the decrease of stability of residual austenite after decomposing during tempering. Reverse transformation from martensite during rapid heating is not a diffusion process [13]. So, formation of austenite from martensite during EPT was a time independent transition, and probably not influenced by the dissolution of carbide. The other reason was less time needed for dissolution of secondary carbide. For the starting tempered sample, most of the carbides except the coarse primary carbides in the as-received steel were fully dissolved during the pre-heat treatment. Although lots of secondary carbides precipitated during tempering, the size of secondary carbides was much smaller than that of the spheroidal pearlite carbides in the annealed sample. Meanwhile, spheroidal pearlite carbides form during annealing, which have higher dissolution temperature than that for secondary carbides, precipitated during tempering. So coarse spheroidal pearlite carbide is more stable thermodynamically, which needs longer time or higher temperature for the completion of dissolution.

In the view of the hardness after EPT or heat treatment, samples after EPT from the starting tempered structure have higher hardness (Fig. 3). And the hardness was stably maintained at about 65HRC around the whole austenitization temperature range during EPT. Although the grain size in M2 samples with two different starting structures can both be ultra-refined by EPT, the hardness of ultrafine grained M2 sample with the starting tempered structure is higher than that of ultrafine grained sample with the starting annealed structure, because more carbides were dissolved during EPT when using the starting tempered structure.

5. Conclusion
The grain size of M2 steel can be refined by EPT, regardless of the difference in starting microstructure used. And the ultrafine grained matrix can both be obtained after EPT. But the formation of ultrafine grained microstructure is at lower peak temperature when using the starting tempered structure. And the pre-tempered M2 samples after EPT have the highest hardness, compared with that obtained after heat treatment or EPT when using the starting annealed structures. Consequently, the method combined the pre-tempering with EPT is a better choice to refine the microstructure of HSS.

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References
[1] Jardin R. T., Tchoufang Tchuindjang J., Duchêne L., et al. (2019) Thermal histories and microstructures in Direct Energy Deposition of a High Speed Steel thick deposit, Mater. Lett., 236: 42-45.
[2] Peng H., Hu L., Ngai T., et al. (2018) Effects of austenitizing temperature on microstructure and mechanical property of a 4-GPa-grade PM high-speed steel, Mater. Sci. Eng., A, 719: 21-26.
[3] Vasilko K. and Murčinková Z. (2016) Tool Life Extension Methods for Cut-off Tools Made of High-speed Steel, Procedia Engineering, 149: 520-525.
[4] Qu H., Liao B., Liu L., et al. (2012) Precipitation rule of carbides in a new high speed steel for rollers, Calphad, 36: 144-150.
[5] Bhattacharyya D., Hajra A., Basu A., et al. (1977) The effect of grain size on the wear
characteristics of high speed steel tools, *Wear*, 42: 63-69.

[6] Yu T. H. and Yang J. R. (2007) Effect of Retained Austenite on GPM A30 High-Speed Steel, *J. Mater. Eng. Perform.*, 16: 500-507.

[7] Lu L., Hou L. G., Zhang J. X., *et al.* (2016) Improved the microstructures and properties of M3:2 high-speed steel by spray forming and niobium alloying, *Mater. Charact.*, 117: 1-8.

[8] Wu Q., Sun D. and Liu C. (2008) Effect of Austenitizing Temperature on Microstructure and Mechanical Properties of Semi-High-Speed Steel Cold-Forged Rolls, *J. Mater. Eng. Perform.*, 18: 952-958.

[9] Nogueira R. A., Filho O. O. A., Souza L. F. M., *et al.* (2006) Grain Size of Commercial High Speed Steel, *Mater. Sci. Forum*, 530-531: 16-21.

[10] Zhang J., Zhao H., Shi Q., *et al.* (2019) Fabrication of Ultrafine Grained High Speed Steel with Satisfactory Carbide Dissolution by Electropulsing Treatment, *ISIJ Int.*: ISIJINT-2018-2774.

[11] Wang Q., Cheng G. and Huang Y. (2018) Morphology and precipitation mechanism of large carbides in M2 high speed steel, *Iron and Steel* 53: 65-71.

[12] Liu B. L., Lü Z. Q., Feng W. W., *et al.* (2017) Precipitation and decomposition behaviors of carbides in AISI M2 high-speed steel with nitrogen and mischmetal, *J. Cent. South Univ.*, 24: 782-788.

[13] Zhang J. T., Zhao Y. G., Tan J., *et al.* (2015) Austenite Grain Refinement by Reverse $\alpha' \rightarrow \gamma$ Transformation in Metastable Austenitic Manganese Steel, *J. Iron Steel Res. Int.*, 22: 157-162.