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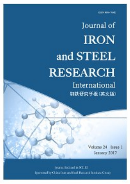

Influence of on-line tempering parameters on microstructure of medium-carbon steel

Hua Zhang, Yan-xin Wu, Jian-xun Fu*, Jie Xu, Qi-jie Zhai

State Key Laboratory of Advanced Special Steel, Shanghai University, Shanghai 200072, China

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ABSTRACT

A new process involving ultra-fast cooling (UFC) and on-line tempering (OLT) was proposed to displace austempering process, which usually implements in a salt/lead bath and brings out serious pollution in the industrial application. The optimization of the new process, involving the evolution of the microstructure of medium-carbon steel during various cooling paths, was studied. The results show that the cooling path affected the final microstructure in terms of the fraction of pearlite, grain size and distribution of cementite in pearlite. Increasing the cooling rate or decreasing the OLT temperature contributes to restraining the transformation from austenite to ferrite, and simultaneously retains more austenite for the transformation of pearlite. It is also noted that bainite was observed in the microstructure at the cooling rate of 45 ℃/s and the OLT temperature of 500 ℃. Through either increasing the cooling rate or decreasing the OLT temperature, the distribution of cementite in pearlite is more dispersed and grain is refined. Taking the possibility of industrial applications into account, the optimal process of cooling at 45 ℃/s followed by OLT at 600 ℃ after hot rolling was determined, which achieves a microstructure containing nearly full pearlite with an average grain size of approximately 7 μm and a homogeneously dispersed distribution of cementite in pearlite.

1. Introduction

Medium-carbon steel, also known as hypoeutectoid steel, usually has a microstructure that consists of proeutectoid ferrite and pearlite micro-constituents. In order to reduce the cost associated with raw materials and manufacture, considerable efforts have been made to displace relatively expensive pearlitic steel with a eutectoid composition, by using hypoeutectoid steel in manufacture of cold drawn wires[1,2]. Unlike ferrite-cementite assembly in pearlite eutectoid steel, which has a coherent crystallographic relationship, Zhou et al.[3] examined the interlamellar crystallagraphy of pearlite in iron-carbon alloys and found that the ferritic-pearlitic structure in hypoeutectoid steels exhibits no such coherent relationship, as proved by Fang et al.[4]. Consequently, due to the deformation mismatch between proeutectoid ferrite and pearlite during cold drawing, voids or microcracks at the interface of two different micro-constituents can be easily formed, which sets the limits for the drawing ability of hypoeutectoid steel. Therefore, a combination of high strength and ductility is needed for hypoeutectoid steel to be an ideal material for cold drawing.

Zheng et al.[5] proposed that one of the effective strategies for simultaneously enhancing the strength and ductility of metals is controlling the volume and distribution of precipitated hard particles in a soft matrix. A number of methods have thus been proposed for improving the distribution of cementite in hypoeutectoid steel. Storojeva et al.[6] applied heavy warm deformation and continuous recrystallization after the γ-α transformation to obtain a homogeneous cementite distribution of a ferritic-pearlitic steel. Yi[7] produced an almost fully pearlite microstructure in a steel with 0.4 wt.% C by slow cooling and controlling the content of manganese and aluminum. Thomas et al.[8] assessed the protential for creating quenching and partitioning (Q&P) microstructures directly from a hot-strip mill and found that Q&P microstructures, containing a significant amount of retained austenite, are also characterized by high strength and ductility, due to the gradual transformation from austenite to matensite during straining, with a consequent increase in the strain hardening rate.

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* Corresponding author. Prof., Ph.D.; Tel.: +86-13701837760.
E-mail address: *fujianxun@shu.edu.cn* (*J.X. Fu*).

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However, quenching and partitioning process may produce many cracks and distortion in the steel, which does harm to the strength and ductility. In addition, on-line heat treatment process, such as austempering process and thermo-mechanical control process (TMCP), also directly governs the microstructure and mechanical properties of the hot rolled steels. Austempering process that steel is austenitized and followed by quenching in a salt/lead bath maintained at a temperature above M_s temperature of the steel, helps in achieving high strength with good ductility by evolving a predominant bainitic/pearlitic microstructure[9,10]. However, it is well established that the lead bath processing is harmful to the environment. On the other hand, TMCP involving ultra-fast cooling (UFC) and on-line tempering (OLT), which reduces the cost and time of manufacture, has been recently adopted to produce low-carbon bainite steel. Chen et al. [11] investigated the microstructural characteristics with various cooling paths in a low-carbon high performance bridge steel based on UFC and concluded that using UFC can effectively refine the size of M/A constituent and promote the formation of lath bainite with high misorientation between laths. Chen et al. [12] also studied a low-carbon bainite steel processed by recrystallization controlled rolling and UFC and found that fine austenite grains are obtained by recrystallization repeated and suppressing recrystallized austenite grain growth using UFC. Tang et al. [13] described the microstructural evolution of high strength microalloyed steels processed using different cooling paths and found that the density of high angle grain boundaries was increased and the average size of precipitates was reduced when increasing the cooling rate. However, there are few reports that discuss the microstructural characteristics of medium-carbon steel with various cooling paths based on UFC＋OLT. It is therefore of great significance to investigate the effects of TMCP, consisting of UFC and OLT, on the evolution of the microstructure.

This study first investigated the continuous cooling transformation (CCT) curves of the tested steel. In addition, the microstructure of the steel during various cooling paths was investigated using an optical microscope (OM), scanning electron microscope (SEM) and electron back-scattered diffraction (EBSD). The optimal process to obtain nearly full pearlite with fine grain sizes and a homogeneously dispersed distribution of cementite in pearlite was determined. Finally, the phase transformation kinetics and the prediction of factors contributing to mechanical properties were elucidated.

2. Experimental Procedures

The steel composition used in this study is given in Table 1. The tested steel was taken from a cylindrical billet after industrial intermediate rolling, with the diameter of approximately 25 mm. Samples for compression were machined from the cylindrical billet to study both the thermal-mechanical simulations and the resulting microstructures. All thermal-mechanical simulation tests were carried out using a Gleeble-3500 thermal simulation machine.

Table 1

Steel composition of medium-carbon steel (wt. %)

C	Si	Mn	P	S	Ni	Cr	Cu	B	Ti
0.35	0.18	0.7	0.01	0.005	0.01	0.025	0.01	0.0015	0.03

To study the dynamic CCT curves of the tested steel, the samples were reheated at 10 ℃/s to 1020 ℃ and held for 5 min for full austenitization, then cooled to the deformation temperature of 850 ℃ and held at this temperature for 30 s to eliminate the temperature gradient. After holding, uniaxial compression deformation was conducted with a reduction of 46%. After deformation, the samples were immediately cooled to ambient temperature at the rates of 0.1, 1, 10, 20, 30, and 50 ℃/s, respectively. Deformation-dilatometer technology was used to produce the dynamic CCT diagram.

In addition, the processes of various cooling paths were simulated based on the dynamic CCT diagram results. The samples underwent the same processes of austenitization and deformation mentioned above, and were cooled with various cooling rates of 18, 25, 45, 65 and 85 ℃/s to the OLT temperature, ranging from 500 to 700 ℃ at a step of 50 ℃, and then held for 90 s. After OLT, the samples were air cooled to ambient temperature. The processing scheme for the experiment is shown in Fig. 1.

Metallographic samples were cut from the tested steel after the process with various cooling paths, and their surfaces in the longitudinal through-thickness plane were polished and then etched in 4 vol. % nital solution for OM (ZEISS Axio Imager) and SEM (ZEISS SUPRA 55) observations. In addition,

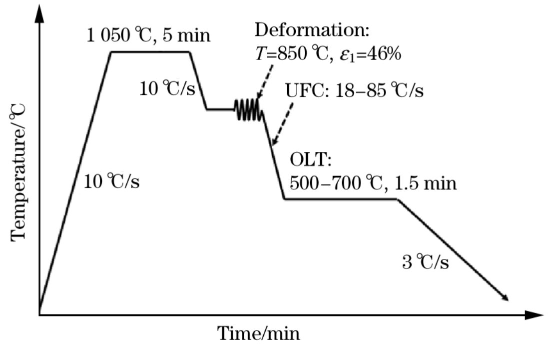

Fig. 1. Processing scheme for thermal simulation experiment.