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Creation of Air-Cooled Mn Series Bainitic Steels

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Abstract: The development and mechanical performances of new type air-cooled Mn series bainitic steels including granular bainitic steels, FGBA/BG duplex steels, CFB/M duplex steels, medium carbon bainite/martensite steels, cast bainitic steels invented by the authors are summarized. The novel series of bainitic steels are alloyed with Mn, and several series bainitic duplex microstructures can be easily obtained under the condition of air cooling through unique composition design. The invented idea, the principle of alloying design, the strengthening mechanism, and the evolution of the microstructure of new type air-cooled Mn series bainitic steels are presented. Furthermore, the applications in different fields of these Mn series air-cooled bainitic steels with different strength level are also introduced. It is suggested that the significance of the development of the air-cooled Mn series bainitic steel can be summarized as follows: reducing costs of both raw materials and production; good combination of strength and toughness; self-hardening with high bainitic hardenability by air cooling from hot working without additional quenching-tempering treatment or quenching procedure; large savings in energy resources; and reduced environmental pollution.

Key words: bainite; bainitic steel; microstructure; mechanical property; air cooling

In 1920, Robertson found the transformation product in middle temperature range called bainite[1]. Pickering et al developed an air-cooled low carbon bainitic steel of Mo series in 1950′s by using the combined influencing of Mo and B on CCT curve[2]. However, high cost of molybdenum and low air cooling bainitic hardenability have limited its applications. In the early 1970′s, under the principle of negligible partition local equilibrium (NP-LE), solute drag, and solute drag-like effect, FANG Hong-sheng et al invented air-cooled Mn series bainitic steels, which changed the traditional idea that air-cooled bainite can only be obtained by the addition of expensive Mo, W, and so on. Moreover, bainitic steel of Mn series have several advantages compared with Mo series: higher air cooling bainitic hardenability, lower bainite transformation temperature (B_s), good combination of strength and toughness, simple alloying and cost saving. Breaking through the tradition that Mo-B series bainitic steel be limited mainly to low carbon field, the present authors invented low carbon, medium carbon, medium high carbon Mn series, and Mn-B series bainitic steels with different properties and applications[3,4]. The aim of this article is to summarize the development and application of air-cooled Mn series bainitic steels.

1 Source of Mn Series Air-Cooled Bainitic Steel

In 1970′s, FANG Hong-sheng et al found that a certain content of Mn may change the shape of TTT-curve[5,6]. Mn has a special redistribution rule in overcooling austenite transformation. To illustrate this rule, $R_{\alpha/\gamma}$ is defined as enrichment factor of Mn in α/γ interphase: $R_{\alpha/\gamma}=X_{Mn}(\text{interphase})/X_{Mn}(\text{average})$, whereas $X_{Mn}(\text{interphase})$ represents the content of Mn in α/γ interphase, and $X_{Mn}(\text{average})$ represents the average content of Mn in alloy.

Correspondingly, R_α and R_γ denote the enrichment factors of Mn in ferrite and austenite, respectively. The experimental results of Mn enrichment factors in certain Mn-B steel are shown in Table 1. No visible difference is found concerning Mn concentration between α and γ phases, whereas there is a distinct enrichment in the α/γ interphase, in accord

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with NP-LE[7]. The concentration spike of Mn is bound to cause pining-up effect on α/γ interphase movement, i. e. solute drag effect, greatly delaying ferrite growth. In addition, Mn enrichment in the α/γ interphase causes the decrease of C-activities and activity gradient in the austenite matrix around the α/γ interphase[7,8] and thus causes the decrease of C-diffusion rate in austenite and further restraint to ferrite growth, which is so-called solute drag-like effect. It is solute drag and drag-like effects that prompt the "bay" shape at 600 ℃ or $\gamma\rightarrow\alpha$ transformation curve [0.13C-Mn (mass percent, %) steel] (Fig. 1). The effects also depress bainite transformation temperature and driving force and fine bainite grain size.

Table 1 Mn enrichment ratio at different temperature

Temperature/℃	R_α	R_γ	$R_{\alpha/\gamma}$
475			1.03
500		1.04	1.07
525	1.01	1.03	1.12
550	1.00	1.00	1.15
575	0.99	1.03	1.19
600	1.00	1.02	1.29
625	1.04	1.00	1.20
650	1.03	0.99	1.24
675	0.97	0.97	1.16
700	1.00	1.00	1.13

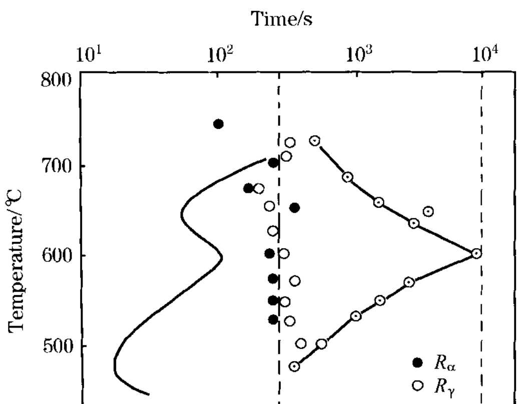

Fig. 1 TTT curve and Mn enrichment ratio *vs* temperature

2 Microstructure Design, Strengthening and Toughening Mechanism, and Application of Air-Cooled Mn Series Bainitic Steels

2.1 Low carbon granular bainitic steel

Habraken[9] suggested that the microstructure of granular bainite consists of ferrite matrix and M/A islands, which was found in low carbon and medium carbon alloy structural steels. The present authors suggested that the so-called "granular bainite" includes two kinds of microstructure, which are not essentially identical (Fig. 2)[10]. One accompanies apparent surface relief effect, where ferrite matrix possessing lath packets belongs to upper bainite ferrite and semicontinuous island strips are distributed almost parallel in ferrite lath matrix. The islands are also distributed preferentially in grain boundary of former austenite, which makes the parent austenite grain boundary apparently. This kind of microstructure is called granular bainite [Fig. 2 (a)]. For the other kind, the striped surface relief effect does not exist, the ferrite matrix is irregular massive pro-eutectoid ferrite; the ferrite matrix may grow up across the parent grain boundary, which is not easy to reveal, and the irregular islands are randomly distributed in ferrite matrix. This kind of microstructure is called granular structure[10,11] [Fig. 2 (b)]. The above mentioned two kinds of microstructures may be separated or mixed, whereas the strength and toughness of the granular bainite is superior to that of granular structure.

Compared with the granular structure, the toughness of granular bainite is better than that on the same strength level because the mechanism of crack propagation of granular bainite is different from granular structure (Fig. 3). The propagation of cracking in granular structure trends to be multichannel, which easily passes through and the resistance of propagation is relatively small.

Mangonon[12] reported that the granular bainite should be avoided because of its harmful microstructure, with which the toughness of steel is decreased. However, the present authors' research suggested that the granular bainite should not be generally defined

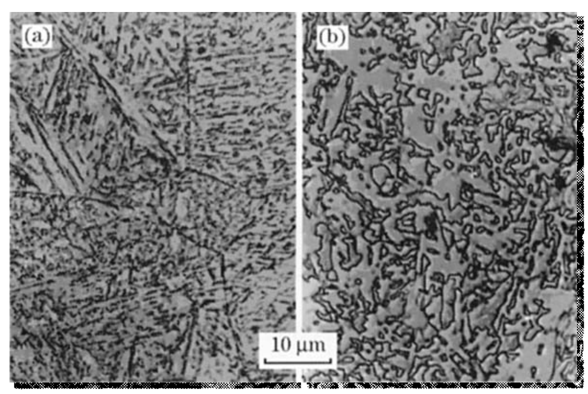

Fig. 2 Microstructure of granular bainite (a) and granular structure (b)