Effects of heterogeneity of Mn distribution evolved during γ reversion on bainite transformation

Kaito Matsumoto[1*1], Goro Miyamoto[2], Miku Watanabe[1*1], Shunichi Nakayama[3], Masao Yuga[3], Tadashi Furuhara[2]

[1] *Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan*
[2] *Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[2]*JFE Steel Corporation, Kanagawa 210-0855, Japan*

The effects of heterogeneity of manganese induced by intercritical annealing on the bainite transformation were studied in a ternary Fe-2Mn-0.1C alloy. To compare conventional 1-step reversion annealing with homogeneous Mn distribution (1-step specimen), 2-step reversion annealing was performed to introduce Mn heterogeneity (2-step specimen), which consists of the first intercritical annealing at 725°C, and the second annealing in γ single-phase. Acicular γ enriched by Mn were mainly formed in the first annealing, and this Mn heterogeneity remained after the second annealing step in γ single-phase region. In the 1-step specimen, carbides and a small amount of MA (Martensite-Austenite constituent) are observed, and MA is distributed between parallel bainitic ferrite (BF) plates. On the other side, in the 2-step specimen, the amount of carbide precipitation in bainitic ferrite decreases and the amount of MA increases compared to the 1-step case, and it is frequently observed that MAs are distributed across BF growth direction. These differences in microstructures between the 1-step and 2-step specimen was discussed from the viewpoints of the effects of Mn content on condition of bainite transformation and cementite precipitation.

Keywords: *austenite reversion, bainite transformation, alloying element*

1. Introduction

A low-carbon bainitic microstructure with high strength and excellent weldability is widely used in thick steel plates for vessels or pipe lines etc. In the manufacturing process of thick steel plates, austenite (γ) stabilizing elements are concentrated in γ during slow heating through ferrite (α) and austenite two-phase temperature range [1]. Such heterogeneity of the alloying elements in γ is supposed to affect the following bainite transformation during the cooling process. However, its actual effects are unclear.

In this study, we focus on manganese (Mn), which addition is essential to improve the hardenability of low-alloy bainitic steels. Mn heterogeneity was introduced by two-step reversion consisting of long intercritical annealing and short annealing in the austenite single-phase region. Subsequently, the specimen was transformed under various bainitic transformation conditions. Through these heat treatments, we aimed to clarify the effects of the heterogeneous Mn distribution on the microstructure formation during bainite transformation.

2. Experiment

Fe-2.0 mass% Mn-0.1 mass% C alloy is used in this study. The hot-rolled plates were homogenized at 1150 °C for 96 h, followed by furnace cooling. The homogenized sample was austenitized at 1100 °C for 600 s, and then quenched into iced brine to obtain a fully martensitic microstructure with homogeneous Mn distribution. Mn heterogeneity was introduced by intercritical annealing in salt bath held at temperatures ranging from 725 °C to 775 °C for 3.6 ks. The annealed sample is subsequently austenitized at 850 °C for 0.6 ks, followed by isothermal bainite transformation at temperatures between 450 °C and 550 °C for various time of periods. The specimens transformed after the two annealing steps are referred to as 2-step specimens whereas the reference specimens transformed from γ with homogeneous Mn distribution with direct austenitizing at 850 °C for 0.6 ks are referred to as 1-step specimens. The microstructures were characterized using Optical Microscope (OM), Field Emission Scanning Electron Microscope (FE-SEM), Electron Back Scattered Diffraction (EBSD), and Transmission Electron Microscope (TEM). Distributions of Mn and C were investigated using Field Emission Electron Probe Micro Analyzer (FE-EPMA) and Three-Dimensional Atom Probe (3DAP).

3. Result

Figs. 1(a) and (b) show SEM micrograph and Mn concentration map of the specimen quenched after the first intercritical annealing step at 725°C measured by FE-EPMA. In this specimen, acicular γ (γ_A) enriched by Mn are mainly formed. The average Mn content in γ_A is 3.25 mass% and Mn content in α (TM : Tempered Martensite) is 1.54 mass%. After the second annealing step in γ single-phase region (Fig. 1(c)), the average Mn content of the area that was originally γ_A is 2.89 mass% and the area that was originally α (TM) is 1.65 mass%. This result indicates that the Mn heterogeneity mostly remains after the second annealing step in γ single-phase region. Fig. 2 (a), (b) shows SEM micrographs of 1-step and 2-step specimens after bainite transformation. In the 1-step specimen, carbides and a small amount of MA (Martensite-Austenite constituent) are observed, and MA is distributed along boundaries between adjacent bainitic ferrite (BF) plates. On the other side, in the 2-step specimen, the amount of carbide precipitation in bainitic ferrite decreases and. volume fraction increases, as seen in Fig. 2(c) compared to the 1-step case. Local composition measurement reveals that MA tends to be located at the high Mn region, which evolves during intercritical annealing. Unlike the 1-step specimen where MAs are formed along BF boundaries, it is frequently observed that MAs are distributed along directions different from BF growth direction in the 2-step specimen.

*1 Graduate Student, Tohoku University

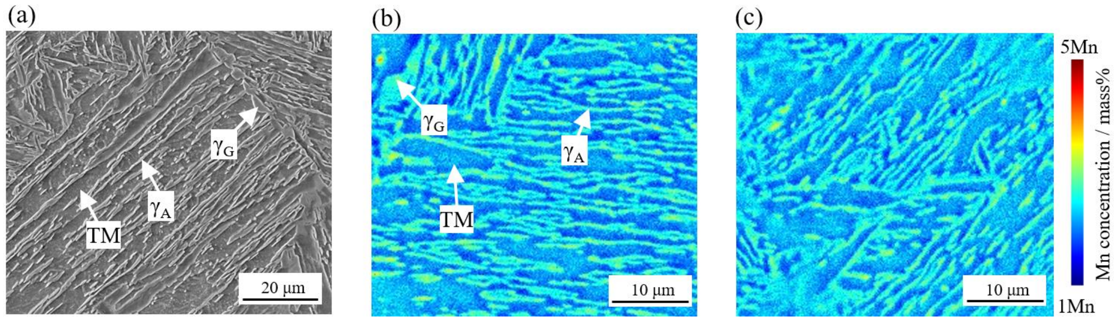

Fig. 1 (a) SEM micrograph and Mn concentration maps measured by FE-EPMA of (b) the specimen after intercritical annealing at 725°C for 3.6 ks, and (c) the specimen austenitized at 850°C for 0.6 ks after intercritical annealing.

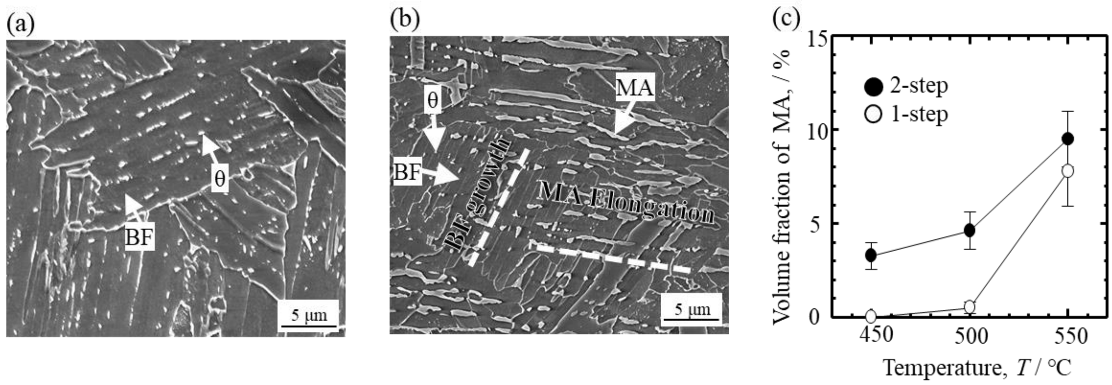

Fig. 2 SEM micrographs of (a) 1-step specimen, and (b) 2-step specimen isothermally transformed at 500°C for 15 s, (c) volume fraction of MA measured by point counting for specimens isothermally transformed for 15 s at different temperatures.

4. Discussion

To explain these microstructure differences between the 1-step and 2-step specimens, the effects of Mn content on bainite transformation and cementite precipitation need to be considered. Fig. 3 shows the isothermal section of Fe-Mn-C phase diagram at 500°C. Red and black solid line represent WB_S composition corresponding to the upper limit for bainite transformation [2] and A_{cm} (para) composition corresponding to the lower limit for cementite precipitate from γ, respectively. A black dot indicates the bulk composition, and a purple dashed line is iso-C activity line in γ passing through the bulk composition. Mn heterogeneity after the second annealing step in γ single-phase region after intercritical annealing measured by FE-EPMA is shown by two green dashed lines. In 1-step specimen, bulk composition is well below the WB_S line, and thus bainite transformation takes place with rejection of carbon into untransformed γ, and carbon content in untransformed γ could approach the WB_S composition. Since the carbon content at WB_S is higher than that at A_{cm}, bainite transformation is accompanied with cementite precipitation in 1-step specimen. In 2-step specimen, driving force for bainite transformation, represented by the gap between the WB_S line and iso-C activity line with respect to the bulk composition, is larger at lower Mn content leading to the preferential bainite transformation in lower Mn region. Carbon rejected from transformed region could enriched into untransformed γ with higher Mn content and consequently, the untransformed γ becomes high Mn and C contents. As the Mn and C concentrations both increase, the driving force for bainite transformation decreases and eventually bainite transformation will be ceased when the composition of the untransformed γ exceeds WB_S composition. Furthermore, when the Mn and C concentration increases high enough that the driving force for cementite precipitation is sufficiently small, the decomposition of untransformed γ with cementite precipitation also will be suppressed. This idea can explain the suppression of carbide precipitation and the increase the volume fraction of MA in the 2-step specimen.

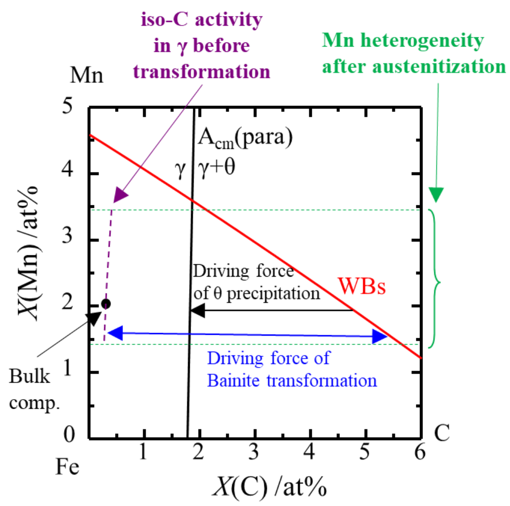

Fig. 3 The isothermal section of Fe-Mn-C system at 500°C

5. Conclusions

The effects of Mn heterogeneity on the bainitic transformation were investigated in a ternary Fe-2Mn-0.1C alloy. The following results were obtained.

1. Acicular γ were mainly formed during intercritical annealing at 725°C, and Mn was enriched into γ. The Mn heterogeneity remained even after annealing in γ-single region.
2. With homogeneous Mn destribution obtained by 1-step annealing, MA is distributed along boundaries between bainitic ferrite plates with carbide precpitation. On the other side, the amount of carbide precipitation in bainitic ferrite decreases, and the amount of MA increases under imhomogeneous Mn destribution by 2-step annealing. These differences can be explained by considering suppression of bainite transformation at higher Mn region as wells as carbon partitioning in γ between high and low Mn regions.

References

1) X. Zhang, G. Miyamoto, T. Kaneshita, Y. Yoshida, Y. Toji and T. Furuhara: Acta Mater. **154** (2018) 1-13.
2) L. Leach, P. Kolmskog, L. Hoglund, M. Hillert and A. Borgenstam: Metall. Mater. Trans. A. **49A** (2018) 4509-4520.