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Effect of Boron Distribution on the Phase Transformation Behavior of Low Carbon Steel Weld Metal†

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Abstract

Abstract
We analysed inclusions formed in low-carbon steel weld metals using focused ion beam transmission electron microscopy. The Al/O mass ratios were varied from 0.28 to 1.63 mass%, and the effects of the Al/O ratio on the inclusions and on the phase-transformation (PT) behaviour were investigated. Our analysis revealed that boron was distributed in the amorphous phase in the inclusions and this strongly affected the PT behaviour of grain-boundary ferrite and acicular ferrite.

KEY WORDS: (Inclusion), (weld metal), (boron distribution), (acicular ferrite), (rain-boundary ferrite)

1. Introduction

Acicular ferrite is a type of ferrite that nucleates from non-metallic inclusions dispersed in weld metals and grows radially from each inclusion. The structure of acicular ferrite consists of interlocked fine grains, which give high strength and toughness in weld metals.
Over the past few decades, numerous studies on acicular ferrite have been published [1]. Nucleation features at the inclusions, sympathetic nucleation and impingement behaviour have been clarified in situ [2]. The role of the inclusions in determining the nucleation behaviour has been the focus of numerous studies. The literature also contains some reports that indicate the formation of acicular ferrite is activated by an increase in the Al/O mass ratio to 1.0. The authors stated that the Si–Mn glassy phase changed to a spinel structure, which has a low misfit value with ferrite, when the Al content was increased. However, Yamada et al. [3] reported that the TiO formed around the surface of the inclusions exhibits a Baker–Nutting orientation relationship to the adjacent ferrite and the TiO layer encourages the nucleation of the acicular ferrite. Although spinel structures are formed, the ferrite interface is not ideal for facilitating ferrite nucleation. Thus, spinel structures have been considered ineffective as nucleation sites.
In this study, to clarify the effect of Al content on the inclusion composition and phase-transformation (PT) behaviour of ferrite in low-carbon steel welds, we investigated the relationship between the microstructures and the inclusions in test pieces with three different Al concentrations.

2. Experimental

The materials used in this study were low-carbon steel welds fabricated by the submerged arc welding process. Table 1 shows the chemical compositions of the weld metals used. Only the Al content was varied, while those of the other elements remained constant. The Al/O mass ratios were 0.28 (B1L), 0.79 (B1X) and 1.63 (B1H). The microstructure, inclusion composition and transformation

Table 1 Chemical compositions of welds (mass%)

	C	Si	Mn	P	S	Ti	Al	B	O	N
B1L	0.062	0.26	1.47	0.012	0.004	0.014	0.005	0.0028	0.018	0.0044
B1X	0.061	0.28	1.51	0.010	0.003	0.017	0.015	0.0026	0.019	0.0036
B1H	0.060	0.25	1.50	0.010	0.004	0.015	0.039	0.0029	0.024	0.0036

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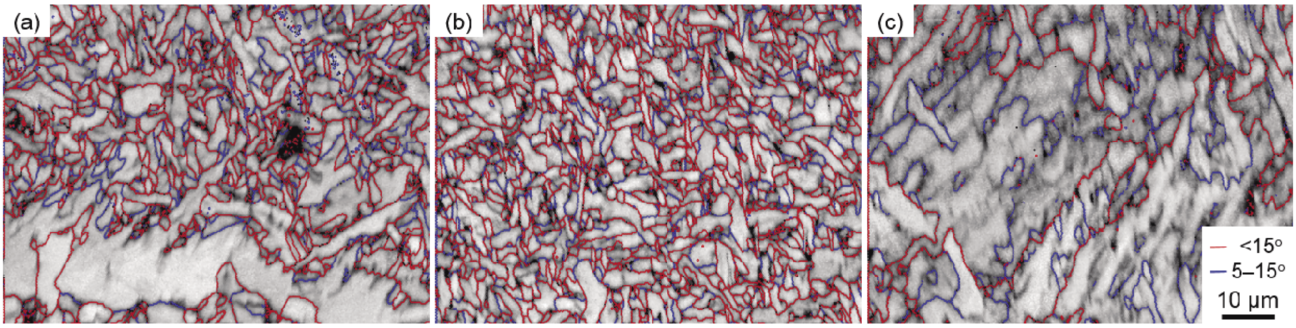

Fig. 1 Image quality maps and grain boundaries: (a) B1L; (b) B1X; (c) B1H.

behaviour of each sample were investigated using the electron-backscatter diffraction method (EBSD), transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDS), high-temperature laser scanning confocal microscopy (HLSCM [4]) .

3. Results and Discussions

Figure 1 shows the results of EBSD analysis. High-misorientation grain boundaries (GBs; >15°) are indicated by the red lines in the image quality maps, and low-misorientation GBs (5–15°) are indicated by the blue lines in the GB maps. Acicular ferrite was formed in B1L and B1X, whereas it was not formed in B1H, where coarse ferrite plates were formed. GB ferrite was observed in B1L but scarcely observed in B1X. The volume fractions of acicular ferrite were 81.5%, 97.1% and 0%, respectively. According to these results, the acicular ferrite exhibited a random orientation, whereas the structures transformed from the prior austenite GBs were parallel orientations. The fineness of the grain size depends on the volume fraction of acicular ferrite.

Figure 2 shows the results of the TEM analyses of the inclusions. In B1L and B1X, the inclusions contained several phases. However, in the case of B1H, the inclusions consisted only of γ-Al_2O_3. Spinel phases, MnS and an amorphous phase were among the phases in the inclusions of B1L and B1X; however, the proportions of the spinel and amorphous phases differed between B1L and B1X. The proportion of spinel phases formed in B1X was substantially greater than that in B1L because of the greater Al content in B1X. In contrast, the proportion of amorphous phase was greater in B1L compared with that in B1X because of the low concentration of the spinel phases in B1L.

Grain-boundary ferrite (GBF) was formed in B1L, but

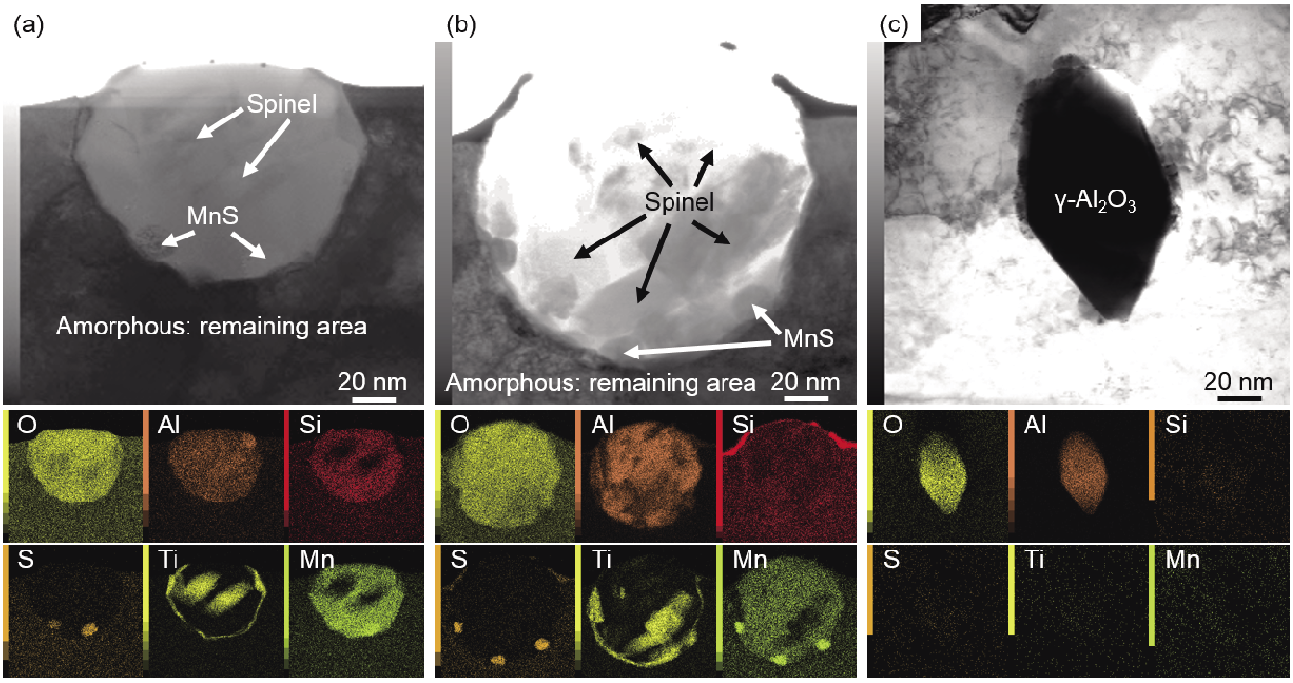

Fig. 2 Bright field images of inclusions and EDS maps: (a) B1L; (b) B1X; (c) B1H.

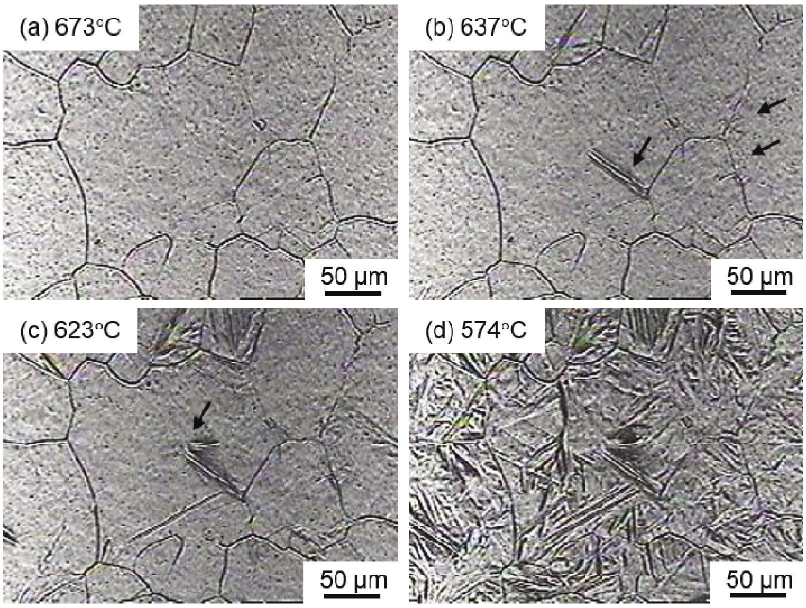

Fig. 3 The In-situ observation of transformation behavior in B1L: (a) 673°C; (b) 637°C; (c) 623°C; (d) 574°C.

scarcely observed in B1X. To clarify the difference between the two, in situ observations were conducted using HLSCM. Figures 3 and 4 show the results of in situ observations of γ/α transformations. In B1L, the transformation started from GBs at 657°C. Then, the intragranular transformation started at 623°C. In B1X, the GB transformation did not occur even when the temperature was less than 640°C. The intragranular transformation started from 627°C and continuously developed.

One explanation of the different transformation behaviours of B1X and B1L is the differences in the effects of the hardenability of boron. Boron is known to significantly increase hardenability even when present at a concentration of just a few ppm. However, boron is difficult to detect using EDS because of its low atomic number; thus, boron is usually detected using electron energy-loss spectroscopy (EELS) [5]. As the report reveals [5], boron was detected only in the amorphous phase. We assumed that in the case of the inclusions

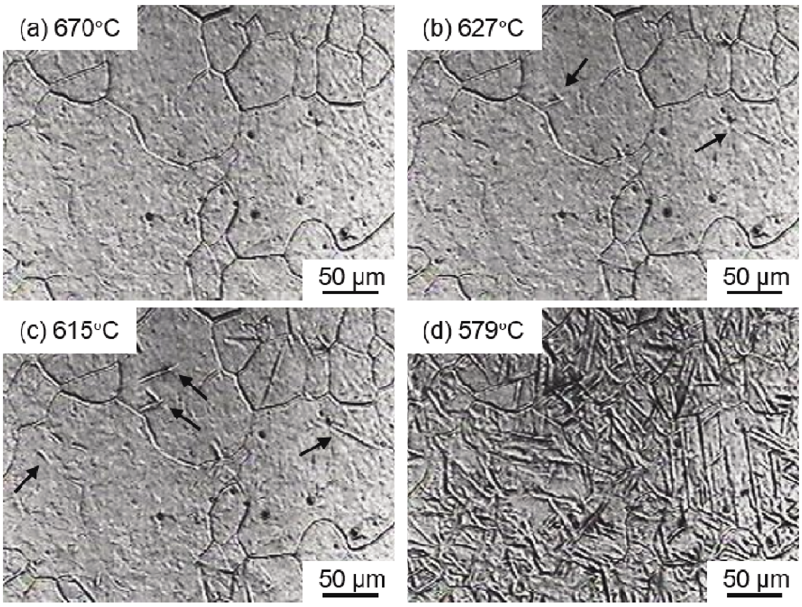

Fig. 4 The In-situ observation of transformation behavior in B1X: (a) 670°C; (b) 627°C; (c) 615°C; (d) 579°C.

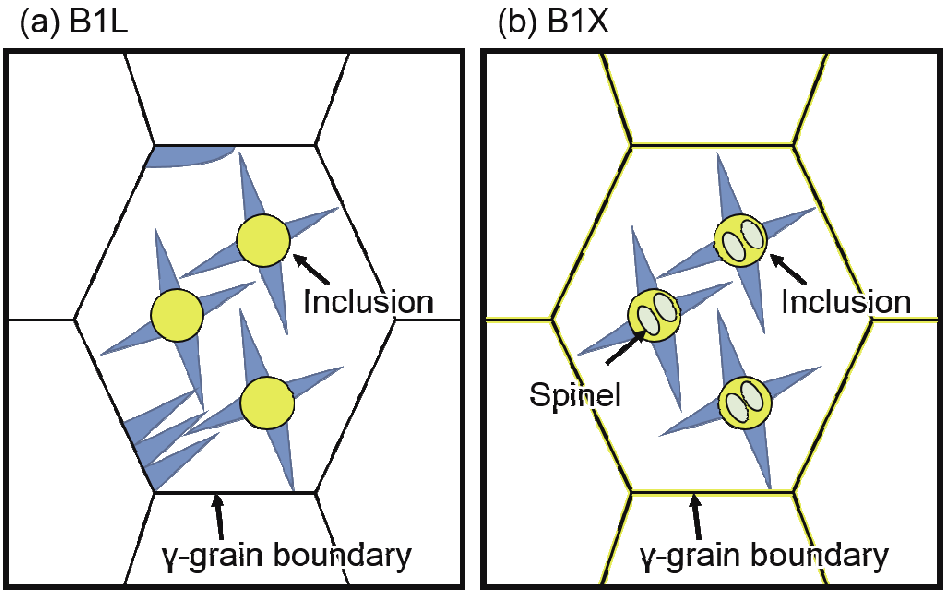

Fig. 5 Schematic illustrations of boron segregation behavior and grain boundary transformation behavior: (a) B1L; (b) B1X.

predominantly comprising an amorphous phase such as B1L, a large amount of boron was absorbed into the inclusions. Consequently, the amount of boron segregated to the austenite GB decreased, which stimulated the formation of GBF. When the Al content was increased, spinel structures were formed, which led to a reduction of the volume fraction of the amorphous phase. When only a small amount of boron was absorbed into the amorphous phase, the boron segregated at the austenite GB before the PT. It suppressed GBF formation and stimulated intragranular ferrite formation. Thus, the relationship between the volume fraction of acicular ferrite and the Al/O mass ratio can be described as the difference in boron segregation behaviour to the austenite GB. The transformation behaviour is summarized in Fig. 5.

4. Conclusions

1) Acicular ferrite was formed in samples with low and medium concentrations of Al, whereas it was not formed in the sample with a high concentration of Al.
2) Increasing Al content promoted the formation of a spinel structure and decreased the volume fraction of the amorphous phase in inclusions.
3) GBF was formed in the low-Al content sample, but scarcely observed in the medium-Al content sample. Through in situ observations, we observed GB transformations in the low-Al-content before intragranular transformations; in contrast, we observed that intragranular transformations were dominant in the medium Al-content sample.
4) We assumed that the formation of an amorphous phase enhanced GB transformation as a result of boron absorption into the amorphous phase, whereas boron segregation to the austenite GB promoted intragranular ferrite transformation with the formation of spinel structures.

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