Lattice Misfit between Inclusion and Acicular Ferrite in Weld Metal of Low Carbon Low Alloy Steel*

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To clarify the mechanism of acicular ferrite formation in low carbon submerged arc weld metals of a Ti-B system with different aluminum contents, the lattice misfit between inclusion and acicular ferrite was investigated. The inclusions were directly sliced into thin foils by a focused ion beam device and crystallographic analyses were performed using a transmission electron microscope. These inclusions were surrounded by a narrow Ti-enriched layer which was identified as TiO. Our results showed that the Baker-Nutting orientation relationship was satisfied between the narrow TiO on the inclusion surface and acicular ferrite.

Key Words: Weld metal, Acicular ferrite, Inclusion, Nucleation, Lattice misfit

1. Introduction

Acicular ferrite is regarded as the most desirable microstructural feature, in view of strength and toughness, in high strength steel weld metals. Therefore, the behavior of the nucleation and growth of acicular ferrite has been extensively studied¹⁻⁷⁾ and the weld metal of refined acicular ferrite is practically used in industry. However, the mechanisms of the acicular ferrite nucleation have been not completely clarified yet.

It is known that inclusions in weld metal strongly contribute to the nucleation of acicular ferrite^{3, 4)}. The previous research result revealed that the inclusions which actually acted as acicular ferrite nucleation sites were multi-phase structure. It consists of amorphous phase of a Si-Mn system, MnS and galaxite spinel MnAl_2O_4 . The lattice misfit between inclusions and acicular ferrite were calculated, but it is not a considerably effective site. However, these inclusions related to acicular ferrite formation were surrounded by a narrow titanium oxide⁷⁾.

In the present work, the narrow titanium oxide forming on inclusion surface was investigated from the crystallographic points of view. The lattice misfit between the narrow titanium oxide and acicular ferrite was investigated.

2. Experimental procedure

The tested materials were low carbon Ti-B submerged arc weld metals with an oxygen content of about 450 ppm. The welding speed and heat input were 0.0217 m s^{-1} and $5.16 \times 10^6 \text{ Jm}^{-1}$.

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Table 1 shows the chemical compositions of weld metals used. The compositions of inclusions were varied by changing aluminum content while the contents of the other elements kept constant. The Al/O ratios (mass ratio) were 0.48, 0.73 and 1.52. It was confirmed that the microstructure of Y1 (Al/O=0.48) and Y2 (Al/O=0.73) consists mainly of acicular ferrite nucleated from inclusions within austenitic grain at elevated temperature and that the microstructure of Y3 (Al/O=1.52) consists mostly of bainite with ferrite laths formed from austenite grain boundaries during cooling⁸⁾. Figure1 shows microstructures of the each samples in room temperature by optical microscope.

To clarify the evolution mechanism, the inclusions were investigated from the crystallographic points of view. The foiled samples including inclusions were prepared with a focused ion beam (FIB) device and were observed with a transmission electron microscope (TEM) which was operated at an acceleration voltage of 200kV. The element analysis of the inclusions was made by energy disperse x-ray spectroscopy (EDS).

Table 1 Chemical compositions of weld metals used (mass%)

	C	Si	Mn	Al	Ti	B	O	N
Y1	0.090	0.35	1.72	0.022	0.014	0.0035	0.046	0.0042
Y2	0.085	0.37	1.75	0.035	0.015	0.0040	0.048	0.0041
Y3	0.086	0.39	1.81	0.073	0.013	0.0040	0.048	0.0035

3. Result and discussion

Figure 2a shows bright field image of inclusion from Y1 in which acicular ferrite was observed. This inclusion mainly consisted of an amorphous phase and partly consisted of MnAl_2O_4 . Figure 2b shows EDS mapping analysis of titanium. The titanium detected on the surface of inclusion. Figures 2c and 2d show an EDS spectrum from the interface between inclusion

a) Microstructure of Y1

b) Microstructure of Y2

c) Microstructure of Y3

Fig. 1 Optical microstructures of the samples by optical microscope

and ferrite. The Cu peaks was caused lay the Cu mesh to support the thin foil. The Fe peak is from the matrix and Al, Si and Mn peaks are from the inclusion. It thought that the C peak is contamination. Therefore, the O and Ti peaks are from inclusion and its surface.

Figure 3a shows a bright field image of inclusion from Y2 in which acicular ferrite was observed. This inclusion consisted of amorphous phase and MnAl_2O_4 . However, the area of amorphous zones was narrow compared to that in the inclusion in Y1. Figure 3b shows EDS mapping analysis of titanium. The titanium was detected on the inclusion surface, similar to those observed in Y1. Figures 3c and 3d show EDS spectra from the interface between inclusion and ferrite. The O and Ti peaks were detected from inclusion surface, similar to those observed in Fig.2.

As shown in Figs. 2 and 3, inclusions contributing to acicular ferrite nucleation were multi-phase particles consisting of MnS,

MnAl_2O_4 and amorphous phases. As reported in the previous study⁹⁾, the MnAl_2O_4 inclusion with a lattice misfit no less than 8.6% and the MnS inclusion with a lattice misfit no less than 7.6% can not be considered to act as an effective nucleation site.

Fig. 2 TEM analysis of inclusion in Y1 **Fig. 3** TEM analysis of inclusion in Y2

4. Conclusions

Transmission electron microscopy (TEM) observations were made to investigate the crystallographic relationship between inclusions and acicular ferrite in low carbon Ti-B weld metals with three levels of Al/O ratio. The findings obtained in the present research are as follows.

- (1) The inclusions which related to acicular ferrite formation were surrounded by a narrow titanium oxide (TiO) layer.
- (2) The Baker-Nutting orientation relationship was satisfied between the TiO layer and acicular ferrite.
- (3) The thickness of TiO layer was 10-20nm.
- (4) The lattice misfit between TiO and nucleated ferrite was 3.0%.
- (5) It can be concluded that the TiO on the inclusion surface contributes to the heterogeneous nucleation of acicular ferrite, supplying low interface energy.

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