Formation of Intragranular Acicular Ferrite Grains in a Ti-containing Low Carbon Steel

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1. Introduction

The formation of acicular ferrite grains from dispersed non-metallic inclusions within austenite grains was proposed as a method for obtaining a refined grain structure in low carbon steels.1,2) The microstructure of acicular ferrite steels consists of fine interlocking ferrite plates originating from the dispersed non-metallic inclusions. This acicular ferrite structure provides a desirable combination of high strength and good toughness because of its small plate thickness and interlocking microstructure.1) In Ti-containing low carbon steels, Ti2O3, MnS, and TiN particles have been reported to be effective nucleation sites for acicular ferrite grains. It was proposed that either Ti2O32,3) or MnS4) among the inclusions is the most effective particles for forming an intragranular acicular ferrite microstructure by producing a Mn depleted zone (MDZ) around the Ti2O3 or MnS particles. For the effectiveness of TiN precipitates, researchers do not agree on their abilities to form intragranular acicular ferrites. One group of researchers reported that TiN can be an effective nucleation site for ferrite grains due to its high coherency with ferrite,5,6) but another group had a contradictory opinion on this.7) More studies aimed at understanding the mechanism of ferrite nucleation at non-metallic inclusions, and gaining the capability of effectively controlling the microstructure and properties of acicular ferrite steels are needed.

The aim of this study is to investigate the formation mechanism of intragranular acicular ferrite grains from inclusions in a Ti-containing low carbon steel with a relatively high N content. The nucleation sites and orientation relationships between ferrite grains and inclusions were investigated using transmission electron microscopy (TEM) and scanning electron microscopy (SEM) equipped with an electron backscattered diffraction (EBSD) system.

2. Experimental Procedures

A 5 kg steel ingot was prepared by vacuum induction melting using electrolytic iron and other high purity materials. The chemical composition of the steel ingot is given in Table 1. The steel ingot was hot rolled and machined into 15 mm cubic specimens. The specimens were austenitized at 1250°C for 15 min by induction heating, cooled at a rate of 3–5°C/s to the ferrite transformation start temperature and then finally water quenched, permitting the formation of intragranular acicular ferrite. The morphology of the intragranular acicular ferrite grains and non-metallic inclusions were observed by SEM (JSM-6330F) after polishing and etching in 2% Nital. The foils used for transmission electron microscopy (TEM) were prepared by mechanical thinning and ion milling using a tripod polisher and a Gatan ion miller. The foils were examined by TEM (Philips CM-20) operated at 200 keV. The orientation relationships between the ferrite grains and the non-metallic inclusions were analyzed in a SEM (JSM-6500F) equipped with an EBSD system (INCA Crystal).

3. Results and Discussion

3.1. Acicular Ferrite Structure

Figure 1 shows the acicular ferrite grains that developed in a specimen cooled at a rate of 5°C/s after austenitizing at 1250°C for 15 min. The microstructure shows the typical features of acicular ferrite steels consisting of fine interlocking ferrite plates originating from the dispersed non-metallic inclusions. One or more ferrite grains first nucleate from the inclusions and these ferrite grains then sympathetically trigger the transformation of the austenite grains into fine interlocking acicular ferrite plates.

Table 1. The chemical compositions of steel investigated in this work. (wt%)

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Ti</th>
<th>O</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel A</td>
<td>0.072</td>
<td>1.9</td>
<td>0.016</td>
<td>0.003</td>
<td>0.007</td>
<td>Bal.</td>
</tr>
</tbody>
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Fig. 1. Optical micrograph of the acicular ferrite structure after cooling at a rate of 5°C/s from an austenitizing temperature of 1250°C.
3.2. Formation of Intragranular Ferrite Grains from Non-metallic Inclusions

Figure 2 shows SEM micrographs of the intragranular ferrite grains formed around the inclusions cooled at a rate of 5°C/s from 1250 to 550°C and then water quenched to room temperature. Figure 2(a) shows a ferrite grain surrounding an inclusion, while Fig. 2(b) shows a number of ferrite grains that formed in association with an inclusion. In both cases, it is believed that these ferrite grains nucleated from these non-metallic inclusions. TEM micrographs of these inclusions and ferrite grains are shown in Fig. 3. Figure 3(a) shows a ferrite grain that formed around a non-metallic inclusion corresponding to Fig. 2(a). It is evident that the non-metallic inclusion has a complex structure, having a round particle approximately 1 μm in diameter surrounded by an almost 1.5 μm square particle.

EDS and electron diffraction show that the round shape precipitate inside is a titanium oxide (Ti₂O₃) while the outside square shape particle is a TiN phase. A small amount of Mg and Mn were detected on the inside of the Ti₂O₃ particle. Figure 3(b) shows an inclusion surrounded by a number of ferrite grains corresponding to Fig. 2(b). EDS and electron diffraction from these inclusions show that the angular inclusion (A) is a TiN phase and the attached inclusion “C” is a MnS phase.

3.3. Orientation Relationship of Ferrite Grains with Inclusions

The crystallographic orientation relationships between the inclusion and the intragranular ferrites (α) were investigated by TEM electron diffraction and EBSD in order to clarify the role of the inclusions in the formation of intragranular ferrites. The electron diffraction patterns from an intragranular ferrite grain accompanied by a TiN particle are shown in Fig. 4. Figure 4(a) is a diffraction pattern from the TiN particle, Fig. 4(c) shows the ferrite phase and Fig. 4(b) shows a ferrite grain including the TiN particle. These
figures show that the intragranular ferrite (α) has a Baker–Nutting (B–N) orientation relationship with the TiN particle ((001)α//(001)TiN, (011)α//(001)TiN). In this orientation relationship, the lattice mismatch across the (011)α//(001)TiN atomic habit plane is 4.7%. This low interface energy configuration is known to promote ferrite nucleation from austenite.

This orientation relationship was also confirmed by EBSD. The secondary electron (SE) image in Fig. 5(a) shows a TiN particle surrounded by a ferrite grain. The pole figure from the ferrite grain and the particle in Fig. 5(a) show that the (001) plane of ferrite is parallel to the (001) plane of TiN, and the (011) plane of ferrite is parallel to the (001) plane of TiN. This relation confirms that the ferrite grain has a B–N orientation relationship with the TiN particle. Figure 5(b) shows a SE image of three ferrite grains associated with a TiN particle. The pole figure from these ferrite grains and the TiN particle show that these ferrite grains have different orientations. However, all three ferrite grains have a B–N orientation relationship with the TiN particle. Considering that Ti2O3 is surrounded by TiN and that the intragranular ferrites formed around the TiN particle have a B–N orientation relationship with the TiN, it is believed that the intragranular nucleation of ferrite grains in this steel is promoted by TiN particles due to their crystal coherency with the ferrite crystal.

It would be worth to mention that the shape of ferrite grains formed around an inclusion with an orientation relationship with the inclusion is more or less equi-axed even though they look very angular. It is believed that intragranular ferrite grains nucleated by an inclusion have orientation relationship with the inclusion that the growth of this ferrite is limited. The acicular ferrite grains formed in austenite grains (Fig. 1) triggered from the ferrite grains formed around inclusions. These acicular ferrite grains do not have orientation relationships with the inclusions but with the austenite matrix.  

4. Conclusions

The role of non-metallic inclusions and the nucleation mechanism of intragranular ferrite grains was investigated by electron microscopy (TEM, EBSD) in Ti-containing low carbon steel. Intragranular ferrite grains are formed from complex inclusions (Ti2O3 + TiN, TiN + MnS). However, the TiN particles are an inclusion that most effectively promotes intragranular ferrite nucleation in this steel. One or more ferrite grains were nucleated from a TiN particle but all ferrite grains have a B–N orientation relationship with the TiN particle. The observed B–N relationship between the intragranular ferrite grains and the TiN particles suggests that the intragranular nucleation of ferrite from these complex inclusions is promoted by the crystal coherency of TiN with ferrite.

REFERENCES

5) Y. Morikage: CAMP-ISIJ, 10 (1997), 1309.