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In-situ observation on the growth of Widmanstätten sideplates in an Fe–C–Mn steel

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ARTICLE DATA

Article history:
Received 2 July 2013
Received in revised form
12 October 2013
Accepted 10 November 2013

Keywords:
Steels
Widmanstätten plates
Sympathetical nucleation
In-situ observation

ABSTRACT

The growth behavior of Widmanstätten plates as well as their lengthening rate in an Fe–0.09C–1.48Mn (weight percent) alloy were examined in-situ on the specimen surface and in bulk specimen by the traditional quench-arrest experiments. Widmanstätten plates directly emanated from austenite grain boundaries and/or from the existing ferrite allotriomorphs, i.e. through the mechanism of edge-to-face sympathetic nucleation. Simultaneously, face-to-face sympathetic nucleation could also occur on the broad face of pre-formed plates. The growth of Widmanstätten plates on the free surface did not occur at a constant lengthening rate but was accompanied by acceleration and deceleration. The average plate lengthening rate measured on the free surface was about one order of magnitude larger than that measured in bulk specimen. The former was close to the plate lengthening rate predicted by the modified Zener–Hillert model assuming paraequilibrium, while, the latter was close to the one that assumes negligible partition local equilibrium.

1. Introduction

Widmanstätten plate is the precipitate which grows directly from a prior austenite grain boundary and/or from a ferrite allotriomorph formed on the grain boundary. The former is termed as primary Widmanstätten plate and the latter is termed as secondary Widmanstätten plate [1]. The mechanisms proposed for the formation of grain boundary secondary plates include morphological instability of the α/γ interphase boundary [2], sympathetic nucleation [3,4], and diffusion–field interaction among laterally moving ledges [5,6]. The studies on the formation of Widmanstätten plates by means of serial sectioning [7,8] demonstrated that the lateral impingement of the neighboring primary plates could also produce the phenomenologically secondary Widmanstätten plates. Recently, in-situ observations revealed that sympathetic nucleation but not the morphological instability of the α/γ interphase boundary was responsible for the secondary Widmanstätten plate formation [9,10]. It was also reported that the edge-to-face nucleation was responsible for the Widmanstätten plate which emanated from the existing ferrite allotriomorph [9,10]. However, there are three configurations of sympathetic nucleation i.e. face-to-face, edge-to-face, and edge-to-edge nucleation [3]. One of the aims of the present study is to determine the possibility of the other sympathetic nucleation configuration for the nucleation of Widmanstätten plates.

In the present study, in-situ observations were made on the growth behavior of Widmanstätten plates, and the lengthening rates of Widmanstätten plates measured by in-situ observations were compared with those obtained in the traditional quench-arrest experiments. Additionally, the experimental lengthening rates were analyzed with respect to the prediction obtained by the modified Zener–Hillert equations.

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1044-5803/$ – see front matter
http://dx.doi.org/10.1016/j.matchar.2013.11.002

2. Experimental Procedures

A low-carbon low-alloy steel, Fe–0.09%C–1.48%Mn, was prepared by vacuum induction melting utilizing high purity electrolytic iron, graphite, and manganese. A 50 kg ingot of the steel was hot-rolled to a plate of 50 mm thickness at 1000 °C and subsequently, the slab was cold-rolled into a steel sheet. Steel specimens were homogenized at 1250 °C for 24 h in a vacuum quartz capsule. The in-situ observation was carried out using a high-temperature laser scanning confocal microscope (LSCM). The specimens were heated at a rate of 5 °C/s, then isothermally held at 1250 °C for 600 s to obtain large austenite grains, and immediately cooled at the rate of 5 °C/s in an infrared imaging furnace in the range of 650 °C to 750 °C with holding time 10 min at 20 °C interval. The LSCM took the 15 optical micrographs per second. Due to the limitations to reach high cooling rate in the present LSCM device, the high temperature austenite was completely transformed into ferrite on cooling to room temperature. Electron backscattering diffraction (EBSD) analysis and the measurement of lengthening rate in the bulk specimen on Widmanstätten plates were conducted on the specimens prepared with the same homogenization temperature and time but isothermally held in the salt bath furnace at different temperatures for variable times and then quenched into ice-cooled brine solution.

3. Calculation of Operative Tie-line

To obtain carbon supersaturation included in the Zener–Hillert model, the carbon concentration at the ferrite/austenite interface at a particular temperature, i.e. the operative tie-line, was calculated. For diffusion-controlled growth theory of ferrite in Fe–C–X alloys, two important modes have been developed. The first is the local equilibrium mode which assumes that full local equilibrium with respect to both carbon and substitutional alloying elements exists at the migrating interface. In this case, the transformation occurs with or without alloying element partition, which are termed partition local equilibrium (PLE) and negligible-partition local equilibrium (NPLE) mode, respectively. The second is paraequilibrium (Para) mode, in which only carbon without any alloying element diffuses during the transformation.

In a ternary alloy, the operative tie-line can be determined by graphical construction because the diffusivities of carbon and substitutional alloying elements vary by several orders of magnitude [11,12]. For PLE mode, the operative tie-line is selected such that the carbon super saturation for growth becomes nearly zero and the moving of the interface is controlled by the diffusion of alloying element. Thus, the $\gamma/(\alpha + \gamma)$ terminus of the tie-line is connected with the bulk alloy composition by the carbon isoactivity line in austenite, as illustrated in Fig. 1(a). For NPLE mode, a tie-line is selected such that the super saturation of alloying element is close to unity. As an extremely thin concentration spike of alloying element is formed, the interface maintains local equilibrium. Thus, the $\alpha/(\alpha + \gamma)$ terminus of the interfacial tie-line is connected with the bulk composition by the carbon-component ray, as shown in Fig. 1(b). In the case of paraequilibrium (Para), the interfacial tie-line passes through the bulk composition Fig.1(c). In the present work, the operative tie-lines, at the interface in ferrite and austenite under the modes of negligible-partition local equilibrium (NPLE) and paraequilibrium (Para) modes, were calculated by Thermo-Calc with the TCFE6 database [13].

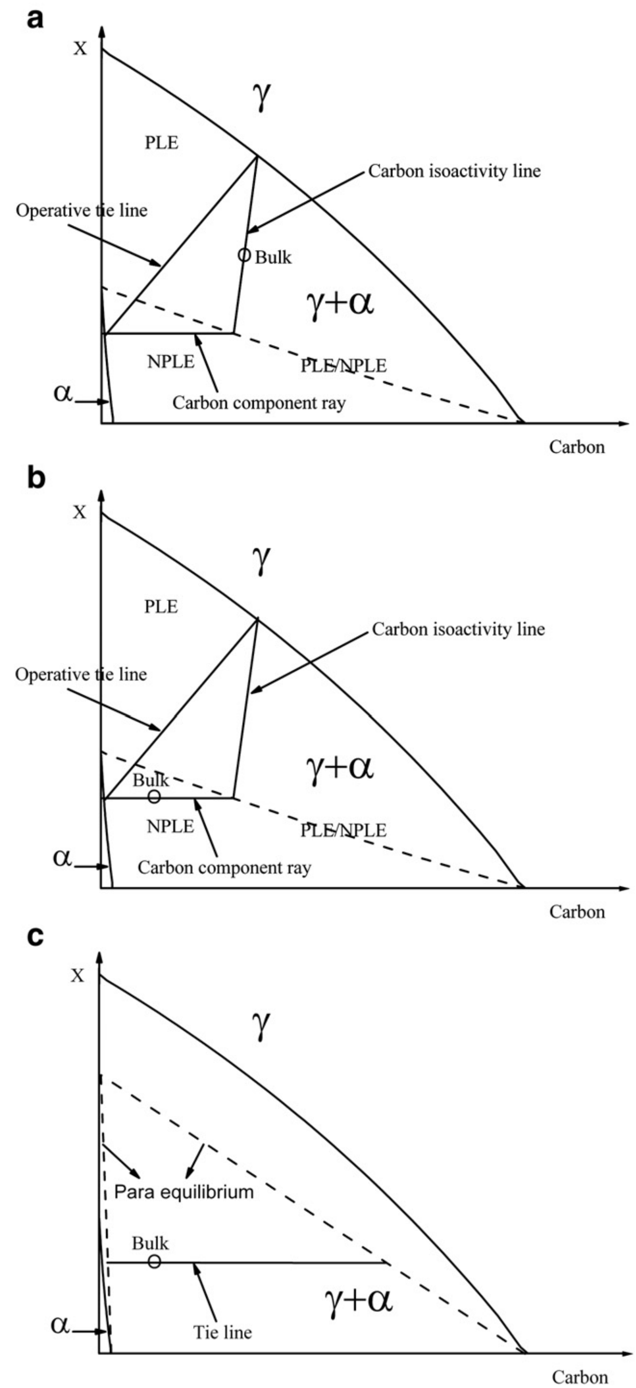

Fig. 1 – Schematic illustration of the construction of local equilibrium interfacial tie-line during ferrite growth in an Fe–C–X ternary alloy, in which X is an austenite stabilizer, e.g. Mn in the present work (a) partition local equilibrium (PLE) mode, (b) negligible-partition local equilibrium (NPLE) mode and (c) paraequilibrium (Para) mode.